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THE EFFLUENT OUTFALL PROPOSED FOR THE FIVE FINGER ISLAND AREA, NANAIMO, B. C.: OCEANOGRAPHIC AND RELATED CONSIDERATIONS

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INTRODUCTION

Local concern over sewage-induced pollution of the waters bordering Nanaimo, B.C. and its environs has been increasing steadily for more than a decade. In response to one recommendation of a survey conducted in March, 1958 to study the problems of sewage disposal in the area, the Greater Nanaimo Sewage and Drainage District (GNSDD) was created in 1959; the area encompassed by the District is shown in Figure 1. The District has overseen construction of the additional facilities deemed necessary by that survey, with the exception of storm-water elimination from the sewerage system. The additions included two outfalls: one - on northern Newcastle Island - discharging into Rainbow Channel, the other discharging into Northumberland Channel near Duke Point (Figure 2); the outflow is crude (untreated). The northern outfall is even now unacceptable for a variety of reasons: shallowness, lack of effective mixing, proximity to highly-utilized bathing beaches, etc. The southerly one is more acceptable at the present time, possessing none of the above disadvantages to any great degree, but it is expected to become of more questionable value in the not-too-distant future.

The recommendations of the 1958 survey were even more modest than those that had been proposed by a similar study carried out in 1956. In addition, the population growth in the area has been extremely rapid subsequent to about 1960 and is expected to continue even more strongly. As a result, the two outfalls have for some time possessed the additional disadvantages of being hydraulically overloaded during prolonged rainy intervals, and indeed are burdened with close-to-capacity flows even when only normal dry-weather input and normal infiltration are received.

Recent policy of the Provincial Government demands the early curtailment of the discharge of untreated wastes to confined shore-waters and the planning by municipalities for provision of adequate sewage treatment facilities. As an indication of the severity of the problem in the Nanaimo area, the Provincial Department of Public Health in late 1968 restricted the number of new connections in the GNSDD until it could be demonstrated that the provision of such facilities was under active consideration. In this connection, a further survey was commissioned by the GNSDD at the end of 1968 and was completed in August, 1969 (Dayton and Knight, 1969).

The philosophy underlying the results of this latest survey was that discharge to the bordering waters (i.e. the Strait of Georgia) is still the only practical method of sewage disposal for the Nanaimo area. It has subsequently been indicated that the sewage treatment and disposal system best

commensurate both with the projected needs for the next several decades and with the attendant financial considerations should involve the construction of a submarine "outlet pipe" discharging treated effluent to the "open" Strait of Georgia (i.e. to "unconfined" waters) at an outfall near Five Finger Island (Figure 2). Upon completion of this system both presently-existing outfalls would be removed, the northern (and less satisfactory) one earlier than the other.

The proposed outfall site was selected on the basis of several considerations: engineering, economic and environmental. The last facet included the examination of all available oceanographic data in the area, including a small amount obtained during the survey conducted in 1958. However, it was felt by those concerned with the planning of the disposal system that more oceanographic field work should be carried out both to assess the proposed discharge terminus more precisely and to suggest, if necessary, a reasonable alternative. In May, 1970, the GNSDD therefore contacted the then Pacific Oceanographic Group located at the Pacific Biological Station, Nanaimo, and requested assistance in the procurement of adequate additional data. The present note deals briefly with the background involved and with the extent and methods of the program eventually adopted. It also summarizes the data obtained during the course of the program and suggests the major conclusions to be derived from these data. (It is to be noted that only <u>sanitary</u> sewage is involved in the considerations under discussion in this report.)

I. GENERAL ENVIRONMENTAL AND ENGINEERING CONSIDERATIONS

Even after sewage has undergone one or more stages of treatment, it must be remembered that the resulting effluent is still not pure water and that adequate disposal of this "residue" must be achieved. As previously noted, it is here accepted that the only practical method of disposal of (treated) sewage from the Nanaimo area is by discharge into the "open ocean" (i.e. the Strait of Georgia) and by subsequent dilution and dispersion. The objective is the preservation of the bacteriological, biochemical and aesthetic integrity of the receiving waters, to a degree sufficient that the full recreational potential, as well as the complete range of useful resources, of the marine area involved may be fully utilized. The purification processes inherent in sea water should enhance the amelioration of conditions within the area effected by the discharge.

The control of sewage-induced pollution must, however, at the same time be as least costly as possible commensurate with the desired objective. To utilize the capability for disposal to its maximum, an adequate study must be made of the receiving area. This study should involve, in the present case, not only the "local" oceanography, but also the associated meteorology (primarily the wind characteristics) and the submarine topography.

A few examples of the considerations involved may be briefly noted. The cost of laying the outlet pipe will be much reduced if the sea bottom in the area in question is character-

ized both by firm mud (or, better, sand) and by a minimum of irregularities such as rocky outcrops. The "basic" water flow in the area should be strong enough to promote adequate dispersion and dilution. On the other hand, currents may, if of sufficient strength, impede seriously the laying of the outlet pipe (and thus increasing markedly the costs involved); however, opposition to such initial "over-costs" should take into consideration the advantages of (properly-directed) strong currents throughout the lifetime of the outfall.

In addition, the longer the pipe (and therefore the further away the outfall from shore) the better in general the chances for continuous high "quality" of the neighbouring shoreline waters. The reasons involve, of course, the enhanced possibilities for dilution and dispersion of the effluent as well as for a greater "die-off" of any pathogenic population associated with the effluent.

In summary, the environmental information obtained should, together with sound engineering practice, ensure best design and placement (in both the horizontal and vertical senses) of the outfall in question. The utmost available resources should be employed in these initial phases; the cost, although it may be substantial, will be more than repaid by aiding in the maintenance of inoffensive and efficient operation of the disposal system in ensuing years.

II. ENVIRONMENTAL FEATURES OF THE AREA CONTAINING THE PROPOSED EFFLUENT OUTFALL

1. Geography and Submarine Topography

The complete area to be serviced by the new sewage facility is on the eastern side of Vancouver Island, and is shown on two scales (Figures 1 and 2). The proposed site of the associated outfall (approximately latitude 49°14.3'N, longitude 123°56.0'W, depth approximately 220 feet (67 metres) at "lowest normal" tides) is given in the latter figure. It is about 5500 feet west-northwest of Five Finger Island. To the immediate west and northwest of the site, the shoreline is extremely irregular, being indented by several small bays and one lagoon; it is faced by several reefs and rocky islets. To the south, the coastline is characterized by topographic irregularities of a much greater scale than those to the north-west and west. These involve Departure Bay and Nanaimo Harbour, and the sizable islands (Newcastle and Protection) helping to shelter these features. Beaches located on these islands, and those associated with Departure Bay, provide a major contribution to the aquatic recreational facilities of the City of Nanaimo. About five miles to the east lies the northwest portion of Gabriola Island; the entire waterfrontage of this island is in great demand for residential and recreational purposes.

To the immediate southeast of the outfall area are the Five Finger Island group and Hudson Rocks; these islands,

especially the latter, are surrounded by extensive areas of shallow waters studded with reefs and banks. This is a major sport-fishing area - primarily for salmon.

The bottom on which it is planned to lay the outlet pipe is believed to be generally of mud, but several rocky outcrops are known to exist. A "shelf" of quite uniform depth (± 60 feet - 18 metres) exists near Hammond Bay. The bottom then deepens gradually to about 220 feet (± 67 metres) - as previously noted - at the proposed outfall site about a mile offshore. Seaward of this the slope becomes much more precipitous; the 600-foot (180 metre) contour is attained in about half a mile, a depth of about 840 feet (250 metres) in a further quarter mile. The bottom then drops away to the main "trench" of the Strait with depths in excess of 1200 feet (360 metres).

2. Tides

In the Strait of Georgia generally, tides are of the semi-diurnal mixed type, providing two high waters and two low waters approximately every 25 hours. They are (lunar) declinational throughout the Strait, the effect being greatest in the southern portion. As a result, they are characterized by a diurnal inequality which affects both their height and their time; the effect is most noticeable in the height and time of succeeding "low" tides. Tides pass through what are termed "tropic" and "equatorial" sequences in alternate weeks. Because

of the declinational effect, these terms contribute to a better description of the tidal régime than do "spring" and "neap", which are otherwise widely utilized. In the former sequence, during which the moon is at or near maximum declination, the inequality is extremely marked.

The largest tidal ranges (differences in height between successive high and low waters) during a tropic tide occur when the diurnal inequality is at a maximum. The largest ranges for the year are encountered during tropic tides when the moon is at its maximum declination (during either the summer or the winter solstices - late June or late December); values as great as 16 feet (5 metres) or more can occur. During the equinoxial periods (late March and late September) the maximum ranges are somewhat less (12 feet - 4 metres). In turn, at any time of the year, maximum equatorial ranges are markedly less than those occurring during adjoining tropic periods; values of 9 feet (3 metres) or less are most common.

Because of the effects of the constrictions at the northern and southern ends of the Strait, tides in the Strait are believed to possess basically the characteristics of "hydraulic" flows. It may be noted that maximum tidal <u>currents</u> in the Strait occur near the midtide range and that slack water occurs at or near high or low tide. Tidal heights may be augmented or diminished by one or more effects, such as wind-induced drift currents (see III below) or movements resulting from horizontal or vertical water-density differences.

No prolonged measurements of tidal height have been carried out in the Nanaimo area. However, it is at present believed that the heights based on predictions for Point Atkinson (Canadian Hydrographic Service, Annual), can, with small error, be utilized at Nanaimo.

Tides and their presumed effects in the Strait of Georgia are discussed at some length by Waldichuk (1957) and by Tully and Dodimead (1957).

3. Winds

Wind stress acting on the sea surface produces a "drift current" in the upper layers of the waters. For the idealized case of a steady wind and homogeneous deep water of effectively infinite extent, the drift at the surface is apparently slightly to the right of the wind direction (in the Northern Hemisphere). The angle between the current and the wind increases within a depth interval determined by such factors as latitude, water density and "eddy" viscosity. (The effect of the wind-induced movement is a net transport of water over the total vertical column to the right of the wind, in a direction approximately perpendicular to that of the wind.) In reality, other complicating factors such as non-steady winds are generally present; this feature, for example, makes the strength of drift currents (as well as of mixing - see below) a function of duration of the wind as well. Also, solid boundaries limit and direct water movement. A few major effects of boundaries

within the area under consideration are noted on page 15.

In mid-latitudes (which case applies to Nanaimo) the magnitude of the "surface" drift (the strength of the drift current) is believed to be about 2 to 3% of the "surface" wind speed.

Another important effect produced by wind stress is the mixing (or stirring) within the water column. For homogeneous water, the depth to which significant mixing occurs is found in practice to be a function of wind speed and latitude. However, if the water density should vary in the vertical, the depth of significant mixing will obviously also become a function of the vertical variation of density (i.e. of the "stability" within the water column). The "stable" situation, of course, has lighter water above denser. An important case involves the presence of a (relatively) thin surface layer bounded beneath by an abrupt increase in density. Such a condition is particularly pertinent, for example, in the main body of the Strait of Georgia adjoining the Nanaimo area. During the freshet period of the Fraser River, freshwater outflow and summer heating at the surface result in a shallow "brackish" layer which can be relatively easily mixed to homogeneity even by light winds. This creates a marked increase in density, and thus great stability, at the lower boundary of the layer. Both theory and observation suggest that any wind-induced drift current will be essentially confined to this layer and should attain a maximum value more quickly than in the case

of deep, homogeneous water. The light water should essentially slide over the deeper water, which will remain practically unaffected. One result should be an appreciable decrease in current strength as one passes from the shallower to the deeper layer. Any thickening of the surface layer will necessitate an intensification of wind strength - compared to the case for homogeneous water; it will also entail a diminishment of the density increase just beneath the layer itself.

The winds in the open Strait of Georgia are believed to result basically from such semi-permanent large-scale meteorological features as the North Pacific "high-pressure" region and the Aleutian "low-pressure" region. The effect of these features would be to provide winds essentially "longitudinal" (i.e. along the main axis of the Strait), predominantly northwest in summer and southeast in winter.

However, the totality of wind régimes believed actually to occur within the Strait throughout the year is somewhat more complicated than the above pattern, especially throughout the southern portion (and thus, presumably, the waters adjoining the Nanaimo area). In spring, winds are predominantly east to southeast throughout the Strait. Southerly (east or west) movement appears to prevail during the summer within the southern part of the Strait. In autumn and winter, there is evidence of a closed counterclockwise circulation approximately south of a line between Nanaimo and Vancouver. This would suggest confused winds within the Nanaimo area during this period, characteristics

varying according to the strength and extent of this "gyre"; it would appear that either northerly or southerly winds could prevail at various times. (However, winds in the Nanaimo area, as elsewhere along the coasts of Vancouver Island, are, in general, "modifications" of the winds in the open Strait. Modifying agents include (diurnal) land- and sea-breeze effects and the irregular topography.)

Gales in advance of sharp meteorological "fronts" blow generally from the southeast; such gales usually occur in winter.

The "immediately-offshore" winds in the Nanaimo area are at present monitored at Entrance Island (Figure 1). Measurements were also carried out from 1930 through 1939 and then discontinued; they were resumed in April 1970. To provide some information on wind conditions likely to be encountered within the area, Table I provides some of the wind characteristics noted from hourly values obtained throughout 1971. On the basis of these data at least, the prevailing <u>direction</u> is apparently east and/or southeast in the area during much of the year (primarily in the autumn and winter - October through April) with westerly directions being more prominent during the summer. The <u>strength</u> (total mileage) of the wind is not always greatest in the direction of greatest frequency (e.g. December). There are very few prolonged periods of calm during any month of the year. Monthly-mean wind mileage associated with the prevailing directions are indicated to be, as would be expected, largest during the winter.

III. OCEANOGRAPHIC CONSIDERATIONS

The oceanographic factors of prime importance for the subsurface placement of a sewage treatment plant outfall are considered here to be the horizontal flow régime and the vertical distribution of density (i.e. the degree of vertical "stratification"), especially within the immediate area involved. The former feature will govern both the strength and direction of movement of the effluent away from the immediate vicinity of the outfall, while the latter will determine the "availability" of the effluent for horizontal motion at various depths, as well as possibly providing an "indicator" of the presence of effluent in the (near) surface waters.

Up to the time of the present work, a negligible amount of oceanographic data (either on currents or on water properties) has been obtained within the relevant area itself. However, some field work has been carried out in adjacent waters (e.g. Departure Bay). A few of the more salient findings are noted here, as they are believed to be of significance both in the choice of the most efficient experimental set-up for obtaining data within the area and in any study of the interaction between the area and the acjoining waters. In addition, brief mention is also made of several "local" features which are likely to affect water movement.

It has been suggested (Waldichuk, 1957) that there is a basically counterclockwise net surface circulation in the Strait of Georgia, with motion on the eastern Vancouver Island side (and

thus offshore of the Nanaimo area) being therefore in a south-easterly direction. The mean speed is considered to be a small fraction of a knot. Tully and Dodimead (1957) indicate general southerly motion for the central and southern portions of the Vancouver Island side of the Strait during ebb tides, but basically weak motion throughout the entire central Strait during flood tides. Such basically qualitative conclusions have been based primarily on hydrocast data of relatively low spatial and temporal density.

Direct current measurements of appreciable intensity in time have been carried out in the Strait since only about 1963. Results obtained about 4 miles north of Nanaimo indicate that currents at all depths can vary appreciably both in direction and in speed from day to day, and can even at times behave independently of tidal action (Huggett, 1966) - all this in the absence of wind. It may be noted that surface and subsurface currents appeared generally to be of the order of 0.5 knot or less. Such behaviour and speeds are also suggested by more recent sampling conducted in locations further removed from the Nanaimo area; at depth, currents possessing effectively "unidirectional" motion for times of the order of a week or more have been recorded (Tabata *et al.*, 1971); at other times, directional characteristics indicate that tidal motion predominates.

Surface movement in Departure Bay, just to the south of Five Finger Island, appears to be dominated by wind, with water moving out of the bay in a basically clockwise mode during

southeast winds and into the bay clockwise during northwesterlies. When winds are very light or non-existent, the motion within the bay can become confused, tidal effects presumably contributing to the motion to some significant degree (Tully and Waldichuk, 1953).

Topographic features in the Nanaimo area would appear to have an effect upon the "local" circulation. The presence of Five Finger Island, Hudson Rocks and numerous reefs and shoals implies that at any time eddies - of various sizes and "strengths" - generated by these obstacles - can be embedded in the "mean" flow. The associated turbulence may be of importance in vertical transport of water (page 17).

Several possibilities for the effect of wind on the circulation exist. The most obvious effect will be on the horizontal surface movement. Southeast winds are almost certain to drive surface water from the area of the proposed outfall northwestward toward Nanoose Bay (a small indentation about 10 miles northwest of the area) and the beaches just to the southeast. Northwesterly winds, on the other hand, could direct water onto the mud flats comprising the southern portion of the Nanaimo Harbour area or onto the northern end of Gabriola Island. Onshore (northerly or northeasterly) winds could move surface water from the outfall site directly shoreward; if such water is sufficiently contaminated, it could adversely effect any shellfish populations in the vicinity. Vertical water motion could be affected also. Offshore winds would tend to move nearshore

surface waters toward the main body of the Strait; this in turn could result in the replacement of such water by deeper water undergoing shoreward (horizontal) and then vertical motion.

Unpublished data obtained in deep water a few miles northwest of the outfall area suggest the presence in summer of a relatively light surface mixed layer 30 to 60 feet (10 to 20 metres) in thickness; this "brackish", warmer layer results as a "background effect" both from freshwater runoff (primarily from the Fraser River) into the Strait and the retained heat of summer insolation. Isolated surface "clouds" of even fresher (less-mixed) water can at times migrate across the Strait from the mouth of the Fraser River and influence, temporarily at least, the shallower layers in the Nanaimo area. The waters immediately below the surface layer are characterized by a marked "<u>pycnocline</u>" (a relatively large <u>increase in density</u> within a small depth interval) which separates this layer from the colder more saline waters below. In the winter the mixed layer is generally indicated to be much thicker, of the order of 150 feet (50 metres) or more. Water in this layer, therefore, will be colder and more saline (and therefore denser) than that characterizing the "summer" layer. Contributing factors are mixing by the strong winds characteristic of the season and by convective overturn induced by surface cooling.

It can be noted that effluent should, upon discharge into the sea at depth, be effectively fresh water and may also be of considerably higher temperature than its surroundings.

Thus, the effluent will, as well as being transported and dispersed by whatever horizontal motion exists, tend to rise. Because of "entrainment" of surrounding sea water, the effluent will, during its rise, undergo dilution and tend, therefore, to become more dense. Because of this increase in density, it may, therefore, in summer, be unable to penetrate strongly into the light surface mixed layer and attain the surface. From the point of view of such recreation as swimming (an important consideration in summer), this is a relatively desirable feature for the general area in question. However, marked vertical current shears (the term "shear" referring here to variations in horizontal current speed with depth) tend to promote vertical mixing and thus to create conditions favourable for such recreation. Also, eddies induced by topographic features (page 15) will, within nearshore areas, tend to break down stratification.

The water characteristics, therefore, suggest that the traces of effluent would be more likely to reach the surface during winter than during summer. However, dilution, at least throughout the water column, can be expected to be more intense in both the horizontal and vertical directions, because of several factors such as more vigorous vertical mixing and greater horizontal transport of surface water by wind, and the greater depth interval likely to be traversed by the effluent. In any case, the major recreational activities involving "human-water contact", such as swimming, are at a minimum during this period.

Also to be borne in mind is the possible effect of effluent on marine life. The possibility of deleterious effects upon shell-fish has already been noted (page 15). A perhaps more important reason for sufficient dilution and treatment of sewage discharged into Nanaimo waters is, as also previously noted, the existence of a sizable, essentially "year-round", sports fishery, especially in the Five Finger area itself. The effect upon the fish involved (primarily spring and coho salmon) may be not only "direct" but also "indirect" - such as an influence upon the food supply (e.g. zooplankton).

TECHNIQUES

I. MEASUREMENT OF WATER MOVEMENT

The measurement of currents (surface and/or subsurface) was carried out by three methods:

1. Free-floating current followers
2. Current meters "cable-bound" to shipboard ("Profiling" current meter)
3. "Shelf-contained" current meters isolated from shipboard.

They are listed above in order of increasing sophistication and data-gathering capability. (The first technique is basically different from the remaining two.) Each is described briefly below.

1. <u>The Free-Floating Current Follower</u>

Measurement of "water-parcel" paths or "trajectories" (i.e. "Lagrangian-type" determinations) were carried out by use of devices "following" the water motion. Each such device (or "current follower") consists of an underwater portion (or "drogue") of large area suspended beneath a surface buoy, or "float", which serves as a "surface" indicator of the drogue's position (Figure 3). The drogue itself consists of an 8 foot-long by 6 foot-high sheet of 4 mm polyethylene rigidly supported at top and bottom (Terhune, 1968). (It is to be noted that the current measured is therefore basically an "integrated" value for a 6-foot depth interval.) The sheet aligns itself essentially perpendicular to the flow direction. The float is made of styrofoam shaped into a double paraboloid of revolution, having a diameter of 14 inches and a thickness of 5 inches. These dimensions provide good sea-keeping qualities to the float, as well as both a high buoyancy-drag ratio and a low drag factor. Analysis indicates that the system should perform satisfactorily in any reasonable wind conditions and in water "shear velocities" up to about 3 knots (Terhune, 1968). (The shear velocity is here defined as the absolute value of the vector difference between the water velocity at the surface and that at drogue depth.)

Vessels that released and then tracked such followers in the present experiments positioned each one by coming along side and determining the location - by means of radar on the

larger, sea-going vessels, or by sextant on the smaller vessels (which did not carry radar). By day, a follower could be identified by a numbered "fluorescent-orange" plastic flag on a steel rod attached to the float. At night identification was made possible by means of a flashing light (yellow, red, or white) on the rod.

2. The "Profiling" Current Meter

Current velocities obtained by the instrumentation noted in both 2 and 3 are "Eulerian" in nature. Therefore, they actually indicate the characteristics of the water movement at only the sampling location itself; the resultant values obtained over a period cannot, therefore, in general be considered equivalent to the "water-parcel trajectories" obtained by such devices as the current follower described above. Only if the current velocities at any time are uniform throughout the entire water body involved can the two summations be equal.

The profiling was accomplished by use of a Hydro Products 460/465 current meter, which employs a "Savonius rotor" to measure speed and a magnetic compass to measure direction. An "on-deck" display provides readouts of those quantities. The meters were calibrated for direction both before and after the profiling and were considered to be accurate to within $\pm 10^{\circ}$. However, no facilities were available for calibration for speed, and, therefore, the manufacturer's readings were assumed correct; the accuracy was taken to be ± 0.05 knots at speeds greater than

0.1 knot. The profiling was carried out from a wooden-hulled vessel and, therefore, the effect of the ship upon the (magnetic) values of direction was assumed negligible.

3. The "Self-Contained" Current Meter

At the near surface and at a few subsurface depths, current-velocity values were obtained every ten minutes for periods up to about 50 days by means of unattended "isolated" magnetic-tape-recording current meters attached at intervals along an anchored nylon line. At the surface the line terminated in a large buoy, an 8-foot diameter toroid manufactured by Geodyne. This float was both brightly coloured to internationally-agreed standards and equipped with a light and a radar reflector to aid in avoiding collisions between marine traffic and the "string" of current meters. The meter used at the (near) surface was the Geodyne Model A-850. Both the speed sensor (a Savonius rotor) and the direction sensor are mounted within the main body of the instrument. In the work discussed in this note, a speed value was obtained every 15 minutes, each of these being in turn an average of a 15-reading "burst" (1 reading every 5 seconds) to minimize the effect of any wave motion. The direction was measured as a simultaneous recording of the instrument-direction vane orientation (which provides the direction of the current relative to the instrument) and the magnetic compass reading (which provides the orientation of the instrument relative to magnetic north). The manufacturer claims an accuracy in speed of 0.05 knots for speeds less than

1 knot and 0.03 knots for speeds between 1 and 7 knots.

The meter used at subsurface depths was the Aanderaa Model 4 magnetic tape-recording instrument. In the present program, the Savonius-type rotor of the instrument provided an average speed over a 10-minute interval. The current direction was obtained instantaneously by noting the orientation of a large fin relative to a magnetic compass within the instrument housing. (Because of the presence of this "unprotected" fin, it was considered ineffective to use the meter near the surface, as this would involve, for example, interference of the fin with the surface-buoy unit - especially in the presence of appreciable wave motion.) Speeds measurable by the instrument range between about 0.05 and 5 knots; accuracy is believed comparable to that of the Geodyne A-850. The direction is found to be accurate generally to within ± 5°. Both types of meters and the "mooring assembly" used to suspend them are described in greater detail by Tabata *et al.* (1971).

II. MEASUREMENT OF WATER DENSITY

Salinity and temperature profiles were obtained at the proposed outfall site by means of an *in situ* Industrial Instruments Electrodeless Induction Salinometer. Values were obtained at depths of about 7, 16, 23, 33, 50, 65, 100, 130 and 160 feet (ft) (actually 2, 5, 7, 10, 15, 20, 30, 40 and 50 metres (m) - metric depth units being generally used in oceanographic sampling practice). During the two sessions of current

profiling in September 1970, monitoring took place every 6 hours - commencing just after the initial profile taken in each session. Throughout the winter of 1970-71, the monitoring was carried out about once every 3 weeks. From the data, water-density profiles were prepared.

PROGRAM

The general modes of employment of the techniques outlined briefly above are discussed below. (It should be noted that, unfortunately, insufficiencies of both personnel and equipment dictated that the program of oceanographic measurements actually undertaken be extremely modest in light of the considerations advanced, for example, on page 4. In addition, problems with equipment in the field prevented the full data-gathering potential that did exist from being fully utilized.) The efforts expended in obtaining current data are discussed in their chronological order (which was governed to some extent by the times that the various types of instrumentation became available).

I. FREE-FLOATING CURRENT FOLLOWERS

Monitoring by current follower of horizontal water movement at depths of about 6 ft (2 m) - the "surface" - and 30 ft (10 m) - very predominantly the former - was undertaken during two periods in 1970: July 20 through 24 and August 4 through 7.

Tracking of the followers was commenced both in the near-vicinity of the proposed outfall site (primarily) and up to about 2 miles to seaward. The objective was to provide information on the "shallow" mixed-layer flow most instrumental in influencing <u>significantly</u> the dispersion and dilution of any effluent subsequent to its attaining the (near) surface.

1. <u>July 20 through 24, 1970</u>

This portion of the field work was much more intensive than that of the other, later period. The "inshore" followers involved (those released near the outfall itself) were to be tracked by smaller craft - 20 to 30 ft in length - unless they moved steadily and rapidly out to sea. (The capability of these craft could be best utilized if the followers moved either in a northwesterly direction (basically along-shore) or southwestward into the area bounded by Five Finger, Newcastle and Gabriola Islands.)

Limitations of the small craft permitted their use only during daylight hours. From 3 to 6 followers were tracked on each of the five days except July 21; at that time, two small vessels - rather than the usual one only - became available, and a grand total of 10 followers were utilized. All except 3 of the "inshore" followers involved were of the "2-m" variety.

The tracking sessions had been arranged to take place throughout either one "large" flood tide or a combination of two successive large tides (ebb and flood). Horizontal water

movement in the open Strait of Georgia is apparently not always a strong function of tidal range or stage, even in the absence of wind (page 15); it was nevertheless considered worthwhile to test whether such a relationship (of great importance in the dispersal of effluent) might be more apparent at the outfall site (especially in the nearby passages).

The follower "tracks" obtained are displayed in Figures 4 through 9. The relatively large number of followers utilized on July 21 necessitates the use of two figures (Nos. 5 and 6) to display the results for that day. The tracks of the three 10 m followers obtained (one on each of July 21, 22, and 23) are indicated in a single diagram (Figure 9).

The shaded area under each tidal curve in these and all subsequent similar diagrams represents the total tracking time on the day in question, i.e., the period from the first launching to the final retrieval. Logistics and other problems often prevented all followers from being tracked for (approximately) the same length of time during any one day. The "markers" in the track lines represent the results of "position fixes". Generally, inshore followers did not remain unpositioned for more than about two consecutive hours. To avoid clutter in the diagrams, not all the positioning times of each follower have been given; only those of the initial and final locations, together with that of any feature considered "important" to the session, such as the turn of the tide, have been displayed. All times given are Pacific Standard. The numbers listed along the

tracks represent the average speed (in knots, to the nearest tenth) between the two positions involved; the values presented are considered sufficient to indicate the general speed characteristics encountered.

Simultaneously, the tracking of "offshore" followers was undertaken by a larger, radar-equipped, vessel; in these cases both daytime and nighttime tracking could be carried on uninterruptedly. Four such sessions, each involving three or four 2-m followers, were carried out (Figures 10 through 13); each covered one 20 to 24 hour period (approximately one "tidal day"). Portions of some tracks are denoted by dashed lines; these represent "suggested" basic directions for paths of followers either "lost" to the tracking vessel for appreciable periods or completely lost and later found beached. The numerical characteristics displayed for each track are as in the immediately-preceding figures.

"Instantaneous" (one-minute average) values of both wind speed and direction were obtained aboard the larger vessels every hour on the hour. These are listed in Table II. (Winds were not obtainable aboard the smaller craft engaging in the inshore work; it should be recalled, however, that winds from some directions (e.g. northwesterly) might be influenced by such factors as the local topography (page 2).)

2. August 4 through 7, 1970

The two "inshore" sessions during this interval (on August 4 and 5) involved (10-m followers only; four and six followers, respectively, were utilized. Both sessions were carried out over a single, appreciable, flood tide. The results are displayed in Figures 14 and 15. The single "off-shore" session (involving only 2-m followers) covered a 24 hour period (Figure 16); "hourly" wind characteristics were obtained aboard ship during this session also (Table III).

II. CURRENT PROFILING

The objective of the profiling was twofold: (a) to provide more detailed data on the shallower flow than could be obtained by means of current followers, and (b) to provide simultaneous information for the deeper water. This latter information would concern primarily water that would be encountered initially, or soon after, by effluent issuing from the proposed outfall. To this end, the Hydro Products 460/465 current meter was utilized aboard the anchored vessel FRB "Investigator No. 1" to obtain effectively "instantaneous" values of horizontal current speed and direction approximately hourly at the proposed outfall site (position at anchor, $49^{\circ}14.2'$N, $123^{\circ}55.9'$W). Twelve depths were sampled: 2 m, 5 m, and each successive multiple of five down to and including 55 m (see page 22). Two sampling sessions were involved. The first (of approximately 2 tidal days, 2-4 September) produced 52

profiles; the second (8-11 September) produced 61 profiles, although the last 8 were preceded by a major (13-hour) stoppage of measurements, due to inclement weather characterized by winds of 30 to 55 knot speeds.

A pictorial representation of the results - that of the so-called "progressive-vector diagram" (PVD) - is considered to display clearly the salient characteristics of the current recorded at each depth sampled. Such a format is provided for the present work in Figures 17 through 22. For any depth, the successive arrows in the figures each represent a <u>vector</u> value and indicate, by length and by direction respectively, the speed and direction obtained from one "hourly" measurement at the station. Each pair of speed and direction values are considered to be representative of the current velocity during the entire time interval between it and the succeeding pair; under this assumption, the speed scale can, therefore, also be considered as denoting distances through which the water has moved. (Such a scale is supplied for the figures - each of which contains diagrams for several depths; it is to be noted that the scale is not uniform throughout the entire series of these diagrams.) For any depth, the time and date of the initial and final measurements are given; to avoid clutter, only the sampling times at (or near) each multiple of six hours are noted additionally. Each time given is that multiple of 5 minutes nearest the actual time of the reading. The "solid" portions (——) represent conditions on the ebb tide, the dashed portions (---) those on the flood. Hourly values missed because of such

factors as temporary instrument malfunction were provided by linear interpolation (I) between preceding and succeeding values for speed and for direction. The beginning of each calendar day of the sampling period is delineated by a short "hatched" bar. For each depth, the last 8 readings of the September 8-11 period have been displayed near to, but separate from, the main (preceding) body of data.

It will again be stressed that current characteristics indicate in the general case only the water movement past the sampling location (page 20). Thus, they are not to be confused with the "water-parcel" trajectories measured by current followers. Caution must, therefore, also be exercised in ascribing these values simultaneously to areas much distant from the sampling point, especially where significant spatial variability is known (or suspected) to exist. (Such variability might *a priori* be suspected to characterize the area under consideration in the present work. Simultaneous profiling at even one additional location would seem to be of immense value in assessing more definitely the actual representativeness of the current data obtained, but in the present instance such additional effort was ruled out by limitations in resources.) The distance between the initial and final vectors of the sampling period can suggest the net, or resultant, movement of the water past the sampling location throughout that period.

The representations in Figures 23 and 24 provide examples emphasizing the vertical variability of current

characteristics in both time and space. The former figure displays the aggregate of speed and of directional profiles for each of three times within the interval of (assumed) large flood-tidal currents (page 8). The latter provides the corresponding values for the ebb-tidal case. The solid lines indicate the arithmetic means of the values involved.

During the second session (September 8-11) only, it became possible to obtain, just before most of the individual profilings, "instantaneous" shipboard averages of wind speed and direction. The values obtained are listed in Table V, together with "corresponding-hourly" values obtained at Entrance Island Lightstation. The reasons for including these latter data in this table are discussed at some length on pages 36 and 37. As a result of the conclusions inferred there, Entrance Island Lightstation values of wind for the earlier profiling period (September 2-4) are presented in Table IV (the chronology for presentation for the meteorological information for the two sessions thus being kept consistent with that for the current-profiling data).

III. LONG-TERM CURRENT MEASUREMENTS

The current profiling discussed above has provided data at relatively many depths at one location for 2 to 3 day periods. While the results are considered to be extremely valuable, the necessary effort to obtain them (especially as regards manpower) is relatively intensive. On the other hand, the Geodyne and

Aanderaa meters could record effectively every 15 and 10 minutes, respectively, while unattended, and thus by comparison are relatively sparing of ships and of personnel except during the relatively infrequent times of servicing. These instruments can supply considerably more insight into longer-term characteristics of net water movements (of special interest in the mechanics of effluent dispersal). Ideally, a string of such meters at several locations, each sampling at the depths involved in the profiling, would be desirable. Actually obtained was information from two locations. One "station", N-01 (N-1), was situated at the proposed outfall site (very near $49^{\circ}14.2'N$, $123^{\circ}55.9'W$); the other, N-02 (N-2), was situated roughly one-half statute mile NNE of the outfall (Figure 2). The depth at the outfall station is, as previously mentioned, about 220 ft (67 m) while, at the other, the depth is about 810 ft (245 m). It was hoped that, if the more nearshore data revealed unsuitable current characteristics, at least some current data would be available to adjudge the desirability of the deeper location; this latter site might be considered to be in a "still-feasible" location as far as construction costs were concerned. (As it transpired, more data were obtained from N-02 than from the "original" (outfall) location).

The earliest data were obtained (December 1970-January 1971) at the outfall site - from "mid-depth" - 145 ft (44 m) - and near the bottom - 205 ft (65 m). The depths at which sampling was attempted during the spring (March-April, 1971) and summer (June-September, 1971) included the (near)

surface - 10 ft (3 m) - 65 ft (20 m), 130 ft (40 m), 210 ft (65 m), and - at the deeper location - 410 ft (125 m).

The number of current-velocity values (speed-direction pairs) provided by each Aanderaa or Geodyne meter over an approximately six-week period is large (of the order of 6000 for the former - given proper functioning of the instrument - and of 4000 for the latter). Such masses of data make pictorial representation essential for reasonably rapid and coherent evaluation for such purposes as the one with which this note is concerned. The progressive-vector diagram (PVD) already described (page 28) is especially useful; such diagrams are displayed chronologically for Station N-01 (N-1) in Figures 25 through 30(a), and for Station N-02 (N-2 in Figures 31 through 36(a). Because of the larger sampling periods (and thus number of velocity values) involved, the "distance" scales characterizing these PVD's are very much smaller than those of the "profiling" values of Figures 17 through 22. The unit used when these diagrams were prepared was the kilometre (km); it may be noted that one kilometre equals about 0.6 statute mile, and one kilometre per hour equals 0.54 knot. The numbers associated with the plot refer to days of the month; months are separated by a short bar.

Examples of another representation useful for "orientation" of the results into the geographical background are provided in any (b) portions of Figures 25 through 36. These figures indicate effectively the number of current values contained in each 10° "directional" segment, referred to true North

(0°T). These so-called "direction histograms" quite clearly confirm the presence or absence of any preferential current direction during the sampling period. They are displayed only for the subsurface sampling depths.

IV. DENSITY DETERMINATIONS

Density profiles at the outfall site were obtained mostly throughout the summer of 1970. Figure 37 shows the information obtained during that period, which is considered (see e.g., page 16) to be an especially critical one for the "effluent-surroundings" interaction, and the resulting health and aesthetic considerations involved. The few profiles obtained during the winter of 1970-71 are displayed in Figure 38.

DISCUSSION OF DATA

It is intended to seek first the inferences to be drawn about the water density structure at the proposed outfall site. As previously indicated, the characteristics of such structure can be important from the point of view of the present problem, as regards both the degree of retention of effluent in the deeper water and the possible presence of at least two distinct horizontal flow régimes in the vicinity of the site (and the attendant effect upon effluent disposal). A brief discussion of the characteristics of the horizontal motion itself, as revealed by the various methods of measurement, is then carried out.

I. DENSITY STRUCTURE AT THE PROPOSED OUTFALL SITE

In summer, it is indicated that a relatively strong positive pycnocline (i.e. a density increase with depth) occurs generally above about 50 ft (15 m) - Figure 37. Data indicate that both salinity and temperature characteristics (primarily the former) contribute to both the formation and the persistence of this "stable" pycnocline. This density "gradient" may be overlaid by a fairly uniform surface layer; on occasion, however, it may extend effectively to the very surface itself. Both the thickness and the degree of homogeneity of the surface layer are indicated to be primarily functions of the meteorological conditions (wind characteristics, degree of insolation) obtaining in the ("near-past") period prior to the observation. Very low densities are seen occasionally to characterize the surface layer. These are believed to result from the intrusion of low-salinity water (generally as isolated bodies or "clouds") originating from tidal interaction with the large summer runoff from the Fraser River. The density structure is present during all stages of the tide. It appears also that any water-movement characteristics arising from the proximity to shore, such as "wake eddies" in the "lee" of nearby islands, are not intense enough to destroy the major "summer" stratification. Below the strong pycnocline at the outfall site there generally occurs a very gradual increase of density with depth - a slightly stable condition - effectively to the bottom.

These "summer" states of the water column are in strong analogy with those occurring offshore in the more "open" Strait of Georgia.

In "winter", the stratification - especially that near the surface - is greatly weakened or even erased completely (Figure 38). The structure can become effectively uniform from top to bottom of the water column. This again is similar to the condition that generally occurs to corresponding depths in the open Strait, and is a function both of the severity of mechanical mixing by wind and of cooling at the sea surface.

These data have been obtained during seasonal "extremes" ("summer" and "winter"). It may, therefore, be concluded that the density structure in the area of the proposed outfall site is very similar during these times to that occurring simultaneously in the nearby "open" Strait of Georgia. The intervening periods of the year can, therefore, be expected to reveal the "structural" characteristics of the formation or decay of a strong pycnocline, similar to what occurs during corresponding periods offshore.

II. HORIZONTAL CURRENTS

It may first be noted that the measurements of horizontal current will not be discussed in chronological order, but rather in a sequence which is believed to be more logical and useful in developing the results. It has thus arbitrarily been decided to consider first the two 2-day profiling sessions

(September 2-4, September 8-11, 1970); these provide the only available (albeit brief) insight into simultaneous behaviour of the horizontal movement throughout effectively the entire water column at the proposed outfall site. This consideration will be followed by a discussion of the remaining results, eventually within the context of these previous, more (vertically) spatially-dense determinations.

It is believed that an initial digression upon the wind characteristics relevant to the periods of current measurement is in order. As previously mentioned (page 30), it was found possible to obtain, throughout (only) the latter of the two profiling sessions, "instantaneous" wind data hourly aboard the vessel involved. In addition, the wind is monitored at nearby Entrance Island Lightstation (Fig. 1) by the Atmospheric Environment Service. It was, therefore, felt that some comparison of the values recorded at the Station with those from the sampling vessel should be carried out; this would permit determination of the degree of similarity between "simultaneous" values at the two locations, thereby suggesting whether data from the Lightstation could be utilized to represent with any confidence simultaneous conditions during the earlier profiling session at the site.

Winds at the two locations during the later session are listed in Table V. Although the quantity actually recorded was not identical at both places - as is made clear by the definitions presented in the Table - it appears that "simultaneous"

values of speed are extremely comparable. The significant directions recorded at either site during the session were NW, WNW and W. Except during the first 18 hours of the session, it appeared that NW at the Lightstation generally coincided with W at the outfall site and vice-versa; whether this persistent difference was an artifact of the different modes of recording, or arose either from actual differences in the wind or by chance, could not be established. However, the results suggest directional agreement to within at least about 45° for "simultaneous" values of winds within W-NW sector.

It is, therefore, assumed that a similar "correspondence" existed for winds at the two locations during the earlier current profiling session also. The "hourly" winds at Entrance Island throughout this period are listed in Table IV; this numbering of tables preserves the chronological order at least for data obtained during current-profiling sessions.

1. "Short-Term" Profiling at the Proposed Outfall Site

A. September 2-4, 1970.

Considering first the progressive-vector diagrams (PVD's) of current for September 2-4 (Figures 17, 18 and 19), the water movement past the proposed outfall site was - except near the surface - strongly southeasterly throughout the entire session, especially at depths between about 30 ft (10 m) and 150 ft (45 m). Brisk (10-20 knot) southerly winds (SE, SW) prevailed throughout much of September 2 and 3, and it is suggested

that the "drift" resulting from their presence accounted for the northerly movement recorded throughout the surface layer which was found to be of the order of 15 ft (5 m) thick during the session. On September 4, by which time the wind had changed to 10 to 20 knots NW, this shallow flow in turn quickly altered its direction to one roughly consistent with the new wind direction.

In the surface layer, "loops" or exaggerated "kinks" characterized the PVD's. It is suggested that these distinctive features might result generally from tidal action associated with the flood tides during the session; these were of modest (6-7 ft) (2 m) range. (For the "classical" case of tidal influence in the area, a PVD would be characterized by two such "loops" within about a 25-hour period.) However, throughout the main portion of the water column similar features did not occur; motion was essentially unidirectional. The only possible effect of the tide then appeared to be a lessening of speeds during the floods as compared to those comparable ebbs; no significant alteration in current direction occurred.

Below about 150 ft (45 m), there occurred a marked reduction in the net flow for the period, together with some irregularity in direction. The general lessening in speed was presumably due to frictional effects associated with the bottom; in addition, the irregularities appear generally consistent with tidal action. However, in sum, at no subpycnocline depth did the tide appear to influence significantly the overall directional trend.

Except for the "surface-" and "bottom-affected" layer, the PVD indicates a quite uniform "average" flow with depth past the outfall site during the profiling session. Thus, only <u>one</u> basic flow régime was indicated for the main body of water throughout the session.

B. September 8-11, 1970.

The later period of profiling (Figures 20, 21 and 22) was characterized by an initial several-hour interval of little or no wind; subsequently, wind speeds were appreciable - increasing from about 10 to about 30 knots or more (from the NW or W) - at which latter value profiling was temporarily discontinued (late September 10). During the short series of observations carried out after the weather permitted profiling to be resumed, winds still averaged about 20 knots (N or NW).

The bottom of the pycnocline at this time was between 30 and 50 ft (10 and 15 m) depth. To about the latter value, the direction of the motion past the sampling point was southeasterly throughout the session. The strong winds were responsible in materially augmenting the shallow drift past the station, the net motion at 6 and 16 ft (2 and 5 m) being the strongest recorded within the two profiling sessions. At these very shallow depths, any "loops" and/or other irregularities were presumably masked at this time by wind-induced effects. Somewhat deeper, irregularities were superposed on the drift, presumably being due to tidal action associated with the larger floods (of 8-10 ft, i.e. 2-3 m, range) of the session; for the

remaining floods - whose ranges were very small (about 1 ft) - no such effects occurred.

At 65 ft (20 m) and below, the directional characteristics of the flow changed radically, although the actual "linear" distance that the water moved past the site throughout the session did not appear to change very markedly from the values just noted. The trend at the station commenced southeasterly as before, but with the onset of the first "large" flood tide of the session, the flow direction became extremely irregular. The net effect throughout the upper portion of the sub-pycnocline water was a rather abrupt change to a basically southwesterly trend. Toward the bottom, however, perhaps because of frictional effects, the effect was not as dramatic. Thus, there appeared to be two widely-different directional trends each persisting for at least about one day. The larger flood tides, of 9-10 ft (2-3 m) range, the greatest encountered in the two sessions, appeared to have very strong influence on water-movement direction at the time, in the sub-pycnocline region, but not above. Frictional effects are again indicated to act near the bottom.

Thus, it appears that any "immediate" effect of winds - of strength up to about 30 knots at least - did not appear to penetrate into the sub-pycnocline region. The net motion in the absence of wind appeared generally to be southeasterly but with the possibility of being affected at sub-pycnocline depths ("deep" water) by tides of at least intermediate range for the

area. Net movements past the site were markedly reduced under these conditions. Effluent released at depth at the site could apparently remain fairly "localized" for periods of several hours under such conditions.

The above-noted, as well as additional, features of the current profile common to both sessions can also be seen in representations exemplified by Figures 23 and 24. These figures portray the totality of profiles obtained at and near mid-flood and mid-ebb, respectively, for both sessions. It is indicated that, away from the surface and the bottom, the currents recorded on the ebb possessed much less variability in direction than did those on the flood, the mean direction (heavy line) being about 130°T (southwest). The corresponding average for the flood direction had approximately the same value, but was far less meaningful because of the large "scatter" in values at almost every depth monitored.

The variability in speed was found to be generally large throughout the water column, especially - as might be expected - near the surface. However, in the main portion of the water column, the speeds appeared, in general, significantly smaller on the flood, being mostly from 0.1 to 0.3 knots (5 to 15 cms/sec) as compared to 0.2 to 0.4 knots (10 to 20 cms/sec) on the ebb.

The largest (hourly) speed recorded during the sessions occurred at the surface - just over 2 knots ($\sim$ 100 cms/sec); the smallest value, effectively at instrument threshold (0.05 knots

or 2-3 cms/sec), was recorded at 35 m depth at about high water. The largest net motion past the station over a session was about 24 nautical miles, for an average net speed of about 0.5 knots (25 cms/sec). (The "progressive vector" in this case was effectively linear throughout.) Typical "linear" net motions in the deeper water were of the order of 0.3 knots (15 cms/sec) for the sessions. The very irregular motions were associated with net displacements of only 1 or 2 nautical miles in 48 hours, even though the linear distances travelled were comparable to those of the preceding cases.

2. Surface (Layer) Currents

A. "Long-Term" Measurements at the Proposed Outfall Site

One can consider next the "long-term" (up-to-8-week) "point" records of "surface" current (6 ft or 2 m). In these cases, the PVD's reveal a basically easterly or northeasterly net movement past both sampling sites throughout these extended periods (e.g. Figures 27 and 28). At no time was a southerly or westerly trend found to exist.

Embedded in these trends are perturbations of various time scales. Loops, near-loops, and other irregularities of few-hour duration appear to indicate the effect of tidal action. The long-term effect of such action was indicated to be rather small; tides in general appear to be of major significance in establishing or maintaining the "overall" directional trend.

Also present are larger periods (ranging from a few days to about two weeks) in which the directional trend of the flow past the site remains quite constant. There are relatively well-defined "boundaries" between successive periods of this type, characterized by distinct and sometimes very abrupt changes in the trend. Examination of the corresponding "surface"-wind records from Entrance Island Lightstation suggests that many of the significant "shifts" may represent responses to major changes in prevailing wind direction. The directional trends between changes are basically consistent with the relevant winds; due easterly water motions appear to be simultaneous with westerly (W, NW) winds, and northerly motions with southerly (S, SE) winds.

It is indicated that the "directional" results obtained near the "surface" during the profiling sessions are not inconsistent with these long-term results. Embedded within the latter can be seen both effectively undirectional (southeasterly) trends of at least two days' length as well as sessions presumably influenced by a combination of wind and tide - features indicated in the profiling data.

The net distances travelled past the sampling point during the longer periods were found to vary quite widely; values ranged between 200 nautical miles ($\sim$ 370 km) over about 36 days - for an average speed of about 0.25 knots (12 cms/sec), to 800 nautical miles ($\sim$ 1500 km) over about 52 days - for an average speed of about 0.7 knots ($\sim$ 35 cms/sec). The actual

rectilinear distance travelled could be appreciably greater, however, as a result of major irregularities in flow direction, in the latter example, this distance was about 50% greater than the 800-mile value given.

B. Measurements by Current Follower in the General Vicinity of the Site

The foregoing results have indicated some characteristics of the horizontal motion throughout the water column at the proposed outfall site. It would be desirable to obtain, in addition, some knowledge of the "subsequent" behaviour of flow considered to "originate" in the general vicinity of the site (pages 23 and 24); reporting of the effect of various combinations of wind and tide would be of special relevance in the surface waters. Such information obtained in the shallower waters by use of current followers is displayed in Figures 4 through 16. (Unfortunately, monitoring of this type could not be carried out in the deep water in the present survey.)

Surface (6 ft, 2 m) movements recorded during various intervals within a large (about 13-15 ft, 4-5 m) ebb and a succeeding, comparable, flood are indicated in Figures 4 through 6. The monitoring period on July 20 was featured by light variable winds (Entrance Island Lightstation). Flow "originating" near the outfall site slightly later than high water moved almost due south on the ebb, becoming much weaker (although having the same basic direction) on the succeeding flood. This flow attained both the northern end of Northumberland Channel and the

estuarial flats comprising the southern portion of the Nanaimo Harbour area, and in its later stages was strongly influenced by the shoreline. Thus, substantial net motions occurred over the monitoring interval. The flow near the outfall was somewhat greater than 1 knot, decreasing to about a quarter of this near the conclusion of monitoring. The simultaneous "near-shore" flow moved southward, and was initially as strong as the motion just noted; however, it weakened greatly (to about 0.2 knot), thereafter, barely attaining the northeastern shore of Newcastle Island. Movement in Departure Bay was indicated, therefore, to be outward on the ebb.

The ("ebb-flood") monitoring period on the following day was featured by 10-15 knot NW winds during much of the ebb and by comparable E winds during the flood. Thus, on both tides, wind drift would be expected generally to augment the (presumed) tidal flow. Motion originating near the site and to the southeast appeared to be, in contrast to that of the previous day, fairly well correlated throughout with the expected tidal motions - being not only generally southeasterly on the ebb but northwesterly during the succeeding flood. The speeds were usually of the order of 0.4 - 0.6 knots (being somewhat smaller on the floods than that of the previous day); they were somewhat less near the time of the sessions slack water. Net motions throughout the tracking session were modest but tended to the east or north. The flow near the shore reversed near the turn of the tide; however, perhaps because of bottom frictional effects, a clockwise eddy motion was suggested in the final

stages, with the net flow for the session being to the southeast.

Figures 7 (July 22) and 8 (July 23) each deal with motion on a large flood tide only, and were made to discover whether surface movement originating at such times might tend landward. The tide on the 22nd was of somewhat greater range than was the later one. In addition, the session of July 22 was of longer duration than that of the next day. Wind speeds were small throughout both sessions, and thus of little influence. It appears that (flood-tide) motion can be markedly influenced by the presence of Five Finger Island and by Hudson Rocks. Waters moving between these obstacles can apparently be "channeled" either in a northerly (clockwise) or southerly (counter-clockwise) direction. To the "west" ("downstream") of Five Finger Island at least, it appears that "clockwise" eddies can at times be generated; consequent "localization' of water in the area could, therefore, occur temporarily (for, say, several hours). The channeling effect can result at times in motion into Departure Bay from the north; movement can be more linear - directly along the shoreline - north of the Bay. The motion in the area of the Islands and outfall is, therefore, indicated to be much more irregular and of smaller magnitude on the flood than on the ebb (see Figures 4 and 5); however, speeds are found to be comparable to those on the flood elsewhere in the general area.

The few current-follower results obtained at about 33 ft (10 m) are displayed in Figure 9. At the time, this depth

was indicated to be approximately that of the bottom of the pycnocline. One follower was employed on each of 3 days (July 21 through 23). The first day's results (obtained on the ebb and succeeding floods) indicate generally southeasterly motion on both ebb <u>and</u> flood - different from conditions at the "surface" (see Figures 5 and 6) - with some deflection to the east, presumably imparted by the presence of Hudson Rocks and of Snake Island. Speeds were comparable on both flood and ebb (averaging about 0.3 knot generally), with almost no motion during the intervening slack water. The remaining "33 ft" followers also indicated slow but definite easterly motion on the flood; the irregularity that seemed to characterize the simultaneous surface flow was in large degree absent (except for slight defections due to Five Finger Island). Thus, the motion at about 30 ft - still basically within the surface layer - appeared to be in general easterly during <u>both</u> flood and ebb. This contrasted with the somewhat more irregular motion (simultaneous or not) at the "surface".

The results of tracking somewhat more offshore surface flow, for a period of 20 to 24 hours, on four successive days in July 1970 are displayed in Figures 10 to 13. Sessions were commenced on July 20, 21, 22 and 23; all were initiated at low-water proceeding a large 15 ft ($\sim$ 4 m) flood, which was succeeded by a small ebb and flood and a comparable ebb. (The session of July 22, unlike the others, was characterized by negligible wind strengths most of the time; only during the final 5-6 hours did wind speeds reach 10 knots.) The tracking

commenced, except in the one instance noted below, to the north and northeast of the proposed outfall site. The session "commencing" July 20 (Figure 10) was featured by light winds during the first large flood. Water a few miles to the northwest of the site moved northwest until about the end of the first flood. Subsequently, it moved to the southeast and almost into Nanaimo Harbour (although details of the movement could not be ascertained). Presumably the brisk 15-20-knot W and NW winds occurring for much of the remainder of the session contributed to the motion. Movement originally about 2 miles to the north and northeast of the outfall site moved slightly to the northwest (presumably due to flood-tide effect) and then eastward. The "stranding" of one follower on south Gabriola Island, if due to the "elements" only, suggests net southwesterly motion for the period between loss and recovery. Speeds as large as 0.8 knots (averaged over several hours) occurred during the easterly movement.

Throughout much of the session commencing on July 21 (Figure 11), motion to the east and north of the outfall site was easterly. Only near the end of the session was there a significant change in the direction of motion - to the south and, possibly, the southwest. Initially, the (easterly) speeds were slow (of the order of 0.2 knot), but nevertheless easterly, in spite of the presence both of a large flood tide and of 10-knot E winds. Speeds are generally greater (one knot and more) during a 5-hour period of 10-20 knot WNW winds on the morning of July 22.

With winds in effect absent, the motion recorded on July 22-23 (Figure 12) indicated possible response to tide during the initial stages of the session (at which time a large flood occurred). During the remaining time, motion was again easterly throughout the session. Speeds were generally less than about 0.5 knots. (In spite of the 10 to 20 knot SE winds prevailing during the latter part of the session, it appears reasonable to assume that the follower indicating comparatively strong westward motion may have undergone some dragging by a vessel during this period.)

The July 23-24 session suggests confirmation of the presence, within the "offshore" area in question, of general easterly motion - which in this particular instance may have been enhanced in the later stages by 20-knot westerly winds. However, it also indicates the presence of significant "local" variability in flow characteristics within the area. Two current followers suggest very relatively limited movement simultaneous with the appreciable easterly motion registered by one nearby. Even the effect of a large flood tide can be markedly different within a small area.

During August 1970, current followers were tracked at 33 ft (10 m) only. On the 4th and 5th, monitoring was conducted during flood tides only; tidal ranges involved were of intermediate size ($\sim$ 10 ft, 3 m). Winds during both these sessions were generally brisk SE (15-20 knots). The followers were found to be contained entirely with the surface layer and pycnocline.

The movement on August 4 commencing near Five Finger Island and inshore was, in spite of some irregularity, basically westerly (i.e. toward the shore north of Departure Bay); speeds, except those recorded north of Five Finger Island (0.4 knot) were generally 0.2 knots or less.

On August 5, generally northwesterly movement was indicated for water motion inshore of Five Finger Island. Seaward of this, however, the motion was somewhat more irregular - various flow directions being noted in a relatively restricted area.

The one 24-hour offshore tracking session of this period (6 and 7 of August) commenced on a flood tide as did those in July; tidal ranges and sequences were very comparable to those of the earlier sessions. This period was featured throughout by SE winds of 15-20 knots; these appeared to suppress any easterly motion, the water monitored moving basically west or north. Speeds and net distances moved during the session were small; the largest speed recorded was 0.4 knot, and most speeds were about 0.2 knot or less.

C. "Long-Term" Subsurface Measurements at the Proposed Outfall Site

Finally, one can examine the long-term subsurface records obtained. As previously noted, the great majority of these data was gathered at effectively subpycnocline depths - about 65 ft (20 m) and greater. The maximum depth thus monitored was about 140 ft (44 m) at the proposed outfall site -

which possesses a total water depth 220 ft (67 m) - and about 400 ft (125 m) somewhat to seaward.

Over the several-week periods in question, the resultant movement in the deeper water was found generally to be strongly easterly or southeasterly past both locations sampled (e.g. Figures 29a and 32a). The deepest sampling level at the more seaward site, 400 ft (125 m) was well below the general level of the "shelf", upon which it has been proposed to lay the sewage "conduit". It may be noted that the "channelling" effect of the bottom topography in the vicinity would appear to favour net easterly movement at this and greater depths.

There occurred, however, appreciable periods during which the net flow, at one depth at least, can be significantly different in direction from the "prevailing" trend, while simultaneous motion at other depths is not. For example, Figures 25a and 26a indicate, respectively, northeast and southeast flow; the depths in question differ by about 60 ft (20 m).

The characteristics of such differences in overall direction, such as their duration, the depth intervals throughout which they can occur, and what causes them - e.g., the (indirect) role played by wind - cannot be ascertained from the present data.

As in the case of surface flow (page 42), one finds, embedded in the (at least) several-week-long trends in current

direction, "perturbations" associated with various time scales. These are again characterized primarily by relatively sudden alterations in current direction at the sampling site, but often without large changes in the corresponding speeds.

The first, and perhaps the most familiar, features were the loops and other irregularities of comparable duration which were similar to those already alluded to in the discussion on surface currents. These are, of course, indicated to be due to tidal action, and were found at both long-term sampling sites (e.g., Figures 26a and 33a), and generally at all subpycnocline depths sampled. However, they did not, in the majority of records obtained, materially alter the directional trend; there were days at least, moreover, when no such effects occurred, i.e., almost perfect unidirectionality existed - e.g., March 9-12, 1971 (Figure 33a).

There also existed irregularities generally encompassing longer-than-tidal periods and having a much greater effect on the flow (e.g., Figures 25a, 32a and 36a). These were often featured by few-day intervals in which reversals of current direction were extremely numerous, resulting in a greatly reduced net flow past the sampling point throughout any such interval. In some instances, a series of reversals was succeeded by, or interspersed with, short intervals in which the current was highly unidirectional. The net effect was generally one of "reversal" of current direction, the flow past the sampling point being effectively west or northwest in the instances

recorded. Such movements showed up strongly on the associated directional histograms (i.e., Figure 36b). The "complete" period of irregularity can persist for a week or more. However, the present data did not at any time indicate the "long-term" directional trend of motion containing such features to become westerly in nature. Simultaneous long-term records for two or more depths are few in the present work. However, those that were obtained suggested that such irregularities can occur simultaneously throughout appreciable depth intervals - examples being from about 65 ft (20 m) at the outfall site (Figures 25a and 26a), to as much as 330 ft (100 m) somewhat to seaward. The "scales" (of time and space) of such "disturbances" apparently need not alter markedly with depth.

The shallowest subpycnocline PVD's appeared more free of these perturbations than were the deeper ones. However, insufficient data exist to indicate unequivocally whether this was indeed an actual characteristic of the shallower waters.

In Figure 34a is shown the PVD obtained for about a two-week period at a depth of 400 ft (125 m). The data were outputted on a larger scale than were those for the longer-period PVD's in order to maintain both legibility and some standardization of scale for data presentation. The diagram indicates the presence of what were believed to be tidal "loops", even at this depth; the effect of these features, as superimposed on a directional trend, were nevertheless small, and would be scarcely visible on the smaller-scale PVD's. Also

indicated is a longer-term irregularity; the "fine-structure" suggests at least some tidal effects interspersed with quite unidirectional flow.

It is possible that some irregularities of "intermediate" time scale may be induced and/or influences to some degree of tidal action, but they cannot be maintained by this effect alone.

A comparison of these results and those obtained during the profiling sessions indicates, as was the case for the shallower flow, no basic inconsistencies in the features recorded for the deep (subpycnocline) movement by the methods. Both types of record indicate, to the detail possible for the scales involved, periods of unidirectionality interspersed with "major" irregularities. Current-speed values obtained by the two forms of monitoring were basically consistent also.

SUMMARY AND CONCLUSIONS

1. Due to the demands arising from a large and accelerating population increase, the greater Nanaimo Sewage and Drainage District has planned a major expansion of sewage-treatment facilities in the Nanaimo area. Present plans call for primary treatment of the sewage (essentially the removal of floating material and of some of the suspended solids) and chlorination. It is proposed to discharge the residual effluent into the nearby Strait of Georgia, by means of an outfall located in the vicinity of Five Finger Island. The depth of this submarine outfall would be approximately 200 feet (65 m).

2. A physical-oceanographic field program to examine water characteristics pertinent to the feasibility of this location has been carried out. The features of the vertical distribution of density have been monitored during times of seasonal "extremes" ("summer" and "winter") in the immediate vicinity of the proposed outfall site. Horizontal current characteristics at various depths at and about the site have also been studied.

3. The density measurements were carried out on shipboard by means of an *in situ* temperature-salinity meter. Currents were measured by three methods:

1) Hourly vertical profiles were obtained throughout about 2 "two-tidal-day" periods, from a vessel anchored at the proposed site.

2) Surface (-layer) movement in the vicinity of the site was monitored by means of free-floating current followers tracked from ships or boats.

3) Currents near the surface and at selected depths at the site were recorded every 10 minutes for periods of up to seven weeks at a time by moored meters possessing data-storage capability.

Examination of the data obtained has indicated the basic oceanographic features of the area.

4. There exists in "summer" a marked increase in density with depth (a "positive pycnocline") above about 50 ft (15 m) at the proposed outfall site. This density increase with depth (a "stable" condition) is usually overlaid by a shallow near-uniform surface layer; occasionally, however, it may terminate at the surface itself. The characteristics of this change (e.g. the density difference involved) are dependent upon wind, insolation and freshwater input. It is present during all stages of the tide. Also, it appears that any mixing arising from such factors as "wake eddies" in the lee of nearby islands, or "internal waves" associated with submarine topographical features in the vicinity, is not intense enough to destroy this density change.

Below the pycnocline, there generally occurs a very gradual increase of density with depth right to the bottom.

5. In "winter", surface cooling and wind-induced mixing erase the pycnocline and generate an essentially uniform density structure throughout the water column.

6. Throughout the year, the structure at the proposed site appears to correspond to that occuring in the more open portions of the Strait of Georgia.

7. The presence of the "summer" density increase with depth near the surface in summer could be of signal importance in the consideration of effluent disposal by submarine outfall. In general, effluent emerging from the outfall will have a density approximately equal to that of fresh water. A mixture of this and ("dense") seawater entrained from the surroundings will possess a density intermediate between the two; this condition should, in theory, effectively prevent effluent from attaining the light (near) surface water. Hopefully, because of the presence of the pycnocline, the outfall would have little effect upon recreational use of the area (e.g. for swimming, boating, fishing), which is at a maximum during the summer months; by the same token, any effect upon marine life in the surface waters should also be negligible. (There is the possibility of deleterious effects, associated with

constituents of the effluent-seawater "mixture", upon any marine organisms - such as various species of zooplankton - that might congregate at a depth (interval) such as the bottom of the pycnocline. Such effects would of course be a function both of horizontal and vertical motion and of the "purification" processes inherent in seawater - see below.)

8. In winter, recreational use of the waters of the area is at a minimum. In any case, dilution, dispersion and oxidation of the effluent would be enhanced both by wind-induced waves (and currents) and by the surface cooling contributing to the formation of uniform conditions throughout the water column.

9. The direction of the "long-term" (up-to-several-week) shallow flow - that at 2 m (6 ft) - appears generally to be easterly or northeasterly in the vicinity of the proposed outfall site, the characteristic being found both at the site itself and at a location somewhat to seaward. At no time during the present investigation was a long-term westerly or southerly trend found to occur. This flow is presumably characteristic in general of the entire surface layer (when this layer exists).

10. "Perturbations" (irregularities) characterized by sudden and marked changes in flow direction, are found to be

embedded in the long-term trend. Various time scales are involved. Relatively "short-term" (several-hour) perturbations are often (but not always) present; it is suggested that at least some may have resulted from tidal action. They are believed to be of only secondary significance in establishing or maintaining the general directional trend. Corresponding marked changes in current speed are seldom present.

11. There also exist periods (with or without tidal fluctuations included) of effectively unidirectional movement, ranging from a few days to about two weeks in duration. These periods are "separated" by abrupt changes in current direction; again, noticeable changes in the accompanying current speeds are not generally present. At least some of these sharp "jogs" in direction appear to be correlated with "major" changes in surface-wind direction within the area.

12. At the proposed outfall site at least, strong winds (20-30 knot speeds) apparently can, when their effect is "well-developed", completely suppress the effect of tides within the surface (layer) waters.

13. Both at the site itself and somewhat to seaward, speeds in the surface layer are found to be the largest recorded throughout the water column. They still are usually less

than about 1 knot ($\sim$ 50 cm/sec) in the absence of wind; however, values as great as about 2 knots ($\sim$ 100 cm/sec), or somewhat more, have been recorded, and presumably result from the acting in concert of wind-induced, tidal, and any other ("residual") motions. Speeds generally are of the order of 0.3 to 0.5 knot (15 to 25 cm/sec).

14. If a northerly or easterly trend in direction were a more-or-less prominent feature of the shallow circulation in the vicinity of the proposed outfall site, as well as at the site itself, it could be of advantage for the "purification" of any effluent attaining the surface (near the site or not). The benefit would be of importance, for example, with regard to any deleterious "constituents" that are featured by a long "decay" time and are also light enough to remain in the shallower waters for appreciable periods. For such constituents, the feature would permit maximum effect of the various "purification" processes (such as oxidation, sedimentation, bacterial die-off, etc.) to be realized.

15. At both the proposed outfall site and inshore of it, effectively equivalent tidal conditions can, at different times, result in markedly dissimilar surface-layer flows, even in the absence of significant direct wind-induced effects. Periods encompassing at least two tides can display this characteristic. For example, a combination of

a large ebb and a large flood (in that order) can, throughout both tides, move water roughly unidirectionally into the northern end of Northumberland Channel and/or the nearby southern end of Nanaimo Harbour. (The effect of such obstacles to the flow at Five Finger and other islands did not appear to be significant during the ebb tide, at least in the present field work.) Motion can also vary with tide in the "more-expected" fashion ("northwestward" on the flood, "southeastward" on the ebb), but can nevertheless result in a net displacement of water, usually to the eastward. However, such "net" effects at times vary markedly in direction throughout a relatively small area.

16. Surface movement just north of the various islands in the vicinity tends to move northwestward during large flood tides. However, flood-tidal flow "passing" these obstacles apparently can often, if not generally, be strongly modified; the "usual" northwesterly flow is "deflected" by them to a greater or lesser degree in a variety of directions. It is also suggested that, on the flood, surface eddies having a lifetime of at least several hours can form "downstream" - to the north(west) - of the islands. In contrast, eddies are not indicated to occur downstream (to the southeast of the islands) during ebb tides.

17. When the effects of tide are "reinforced" by those of wind and of other factors, it is evident that the surface motion

in the area can in general be one of considerable "small-scale" complexity (both in space and in time).

18. In the light of indicated surface movement in the general vicinity of the proposed outfall site, mention should probably be made of the case of effluent in the surface (layer) near the outfall, i.e. attaining shallow water relatively quickly after issuance from the outfall. This condition could result from, for example, the presence of very slow horizontal motion in the deeper waters and/or of the absence of a pycnocline. (The latter factor might occur in summer because of unseasonable weather, however, it would be present more frequently in winter, but would then, of course, be of less importance "recreationally", as previously noted.) Surface motion such as that actually recorded might lead to temporary "localizations", effluent being confined to a relatively restricted area and thus undergoing appreciably lessened "horizontal" dilution and dispersion. There could also occur, for example, movement into Northumberland Channel within a period of the order of a day, an interval which might be that compared to the time necessary for at least the predominant "purification" factors (such as bacterial die-away) to be significant in their effect. (It may be noted that, although the Vancouver Island shore of Northumberland Channel is the site of a large pulp mill and of some associated industry, the Channel is presently under no serious general environmental

"stress" at the present time - although occasional, short-lived, biologically-distressing events have occurred, presumably due, at least in part, to certain combinations of oceanographic and meteorological factors.) However, both the possible occurrence of, and the accompanying effect of, further "loading" of the waterway by effluent from the outfall should be borne in mind. The same considerations are indicated for "nearshore localizations" of effluent and possible accompanying (temporary) degradation of surface waters; such areas as primary sites for sport fishing would be of concern in this case.

19. A few miles offshore of the site, net surface flow appears generally - even in the absence of direct wind-induced effects - to be easterly or southeasterly for periods at least as long as about 24 hours. There may be some motion to the north or northwest during large flood tides. The net distance travelled during such a period can be of the order of the length of Gabriola Island (∿ 15 miles, 25 kilometres).

20. This easterly motion can be enhanced by any "well-developed" drift generated by strong westerly winds. In contrast, (south)westerly winds can counteract the prevailing drift, with large enough wind speeds (apparently about 15 knots or more) the resultant motion can become very small to the east and can develop a northerly component.

21. Surface speeds associated with this offshore flow are generally of the order of 0.5 knot ($\sim$ 25 cms/sec), but can range from 0.2 ($\sim$ 10 cms/sec) to over 1 knot ($\sim$ 50 cms/sec). In the case of strong counteraction of easterly drift by wind, speeds can be reduced to 0.1 to 0.2 knot over extended intervals of time.

22. Any effluent attaining the surface in the "offshore" area can be presumed in general to remain away from the northern shores of Gabriola Island for a sufficient length of time, and even to be borne into more open areas of the Strait of Georgia. Restricted circulations resulting from a (near) balance of the various current-generating effects could possibly lead to some temporary localizations of effluent. However, such localizations would be considerably more offshore than those previously noted and would, because of this and the time available for purification, be potentially less troublesome.

23. The "deep" water is here considered to be that at depths greater than that of the bottom of the "summer" pycnocline, i.e. about 30-50 ft (10-15 m). All measurements, especially those on a "long-term" basis, indicate that the deep-water flow, both at the proposed site and somewhat to seaward, is generally <u>southeasterly</u> or <u>easterly</u> throughout the year. At the more seaward location, motion at greater-than-outfall depths appeared to be characterized by similar

directions, in fact easterly movement at such depths would appear to be favoured by the local bottom topography.

24. In the presence of a well-developed pycnocline, the deep movement is not affected (directly) by winds - at least by those blowing at speeds of 20 to 30 knots for a day or so. (Presumably, wind-induced motions can extend appreciably deeper in the absence of a pycnocline, e.g. in "winter".)

25. At times, simultaneous motions at levels separated by appreciable distances (several 10's of feet) can possess significantly different directional trends, throughout at-least-several-week periods. The causes of such differences are not apparent from the data involved. However, the corresponding <u>net</u> distances moved past the outfall site, and thus the average speeds during such periods is nevertheless generally very comparable for the two depths.

26. Somewhat similar to the case of surface (layer) flow, the dominant subsurface (south)easterly direction of the "drift" can be characterized by several "short-term" features. In addition, almost perfectly unidirectional motion can be present for intervals of a few hours to a few days. "Perturbations" (irregularities) featured by sudden and marked changes in flow direction can also occur; again, the accompanying speeds usually do not change to any great degree. These perturbations can, of course, modify

the flow direction temporarily, but do not apparently do so over the long term.

27. Those irregularities of shortest duration (a few hours) result presumably to some degree from tidal influence; they can occur at all depths, but are not present at all times (similar to the case of shallow flow, page 10). No clearly-defined relationship between their presence or degree and the ranges of the simultaneous tides have been found in the present data.

28. Over several days a series of reversals, separated by longer intervals than those between tidally-generated effects, can occur. While, again, the speeds in general throughout the reversals do not significantly change, the <u>net</u> distance moved past the site during such a series of reversals can be quite modest. (Such features can at times occur simultaneously over appreciable depth intervals; they have been found to occur in the open Strait of Georgia also.) Thus, any effluent present for some time at a depth (interval) characterized by such conditions could, temporarily at least, be confined to a relatively restricted area (with the possible attendant problems, page 17).

29. At some times at least, a series of such reversals can impart a westerly net motion past the site for a short period. This directional trend, if present to the west of

the site also, would suggest ("deep") water movement from the site to the adjacent shores of Vancouver Island - those just north of the Nanaimo area. If prolonged periods of such conditions did often occur, possible deleterious effects on the shorelines concerned might warrant further investigation (most importantly in summer).

30. The "short-term" profiling carried out in the presence of a pycnocline at the proposed site indicates the presence both of marked unidirectionality and of sudden changes in current direction in the deep water, features consistent with those found embedded in the long-term records.

31. Profiling also suggests that, in the deep water at the site, current direction can possess much less variability on the ebb tide than on the flood, regardless of tidal range. By contrast, current speeds appear extremely variable - in depth and in time - during both flood and ebb tides; long-term records suggest this to be true much of the time. Under such conditions, strong current shears, and their attendant capability for mixing, would not appear generally to be a persistent feature.

32. There appears to be, throughout the main body of the sub-pycnocline water, no significant differences in (average) current speed with depth over the long term. Presumably because of the effects of bottom friction, there can,

however, be a significant reduction in speed within the 30-60 feet (∿ 10-20 metres) nearest the bottom of the site. Speeds at much greater-than-outfall depths somewhat offshore also appear to be featured by currents much smaller than those above outfall depth.

33. Speeds in the deep water at the proposed site appear generally to be of the order of 0.2-0.3 knot (10-15 cms/sec); occasionally values greater than 0.5 knot (25 cms/sec) have been recorded. The smallest value recorded was < 0.1 knot (< 5 cms/sec). At a depth of about 400 ft (125 m), somewhat seaward of the site, current values were generally less than about 0.2 knot (10 cms/sec).

34. The deep horizontal motion will of course be that early encountered by the effluent upon issuance from the outfall. Unfortunately, no current-follower measurements could be carried on in the deep water during the present program; nevertheless, a few "educated" speculations can be made concerning the deep motion at locations away from the outfall site. If the dominant southeasterly trend should persist somewhat to the east of the outfall, water passing the site - and therefore receiving effluent - will approach the northern end of Gabriola Island. In this circumstance, several options for further movement exist: flow north or northeast into the open Strait, along the seaward shore of Gabriola, or into Northumberland Channel - or, possibly a

combination of all of these. Briefly, considering these movements individually, the first would be extremely desirable, at least as regards removal of effluent originating in the "Nanaimo" area. The remaining two could, within a relatively short time - perhaps one to a few days - move water into areas which either are at present, or might become in the not-too-distant future, "ecologically sensitive" - see page 18. As already suggested, the net effect upon such areas would presumably be generally a complicated function of the efficacy of the various "purification" factors and of the dispersing and diluting effects of the deep and surface flows.

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TABLE I - MONTHLY SUMMARY OF HOURLY WINDS, 1971: ENTRANCE ISLAND

MONTH	FREQUENCY IN HOURS											PREVAILING DIRECTION	MEAN SPEED (mph)	MAXIMUM RECORDED HOURLY SPEED	
	Total # of Readings		N	NE	E	SE	S	SW	W	NW	CALM			MILES	DIRECTION
JANUARY	744	A*	1	13	242	220	75	42	102	44	5	E	12.7	43	E
		B*	2	93	3584	2770	714	346	1198	743					
FEBRUARY	672	A	9	10	131	181	39	22	136	142	2	SE	13.6	42	NW
		B	59	120	1692	2403	420	119	1564	2731					
MARCH	720	A	12	15	142	171	81	71	111	114	3	SE	15.0	42	SE
		B	58	48	3451	3078	761	644	1103	1683					
APRIL	720	A	15	13	218	153	70	38	168	37	8	E	11.8	34	SE
		B	64	115	2815	742	513	313	2432	481					
MAY	744	A	18	15	144	72	29	23	312	129	2	W	13.0	36	W
		B	78	61	1571	527	246	161	5263	1795					
JUNE	720	A	12	8	370	124	44	30	92	31	9	E	9.5	39	E
		B	48	41	4217	1051	245	204	728	270					
JULY	744	A	14	16	146	54	31	31	269	178	5	W	10.9	27	W
		B	42	55	1379	394	224	209	3320	2522					
AUGUST	742	A	14	12	238	126	27	25	197	95	8	E	10.0	30	SE
		B	41	43	2887	1067	175	113	1954	1118					
SEPTEMBER	720	A	15	17	157	120	30	27	264	88	2	W	9.9	30	W
		B	45	93	1773	1164	219	147	2875	825					
OCTOBER	744	A	6	10	256	129	36	40	179	86	2	E	13.0	45	E
		B	34	83	4050	1492	264	258	2488	1030					
NOVEMBER	720	A	2	6	264	169	52	31	153	43	0	E	15.1	44	E
		B	18	49	4923	2687	343	171	2247	455					
DECEMBER	744	A	6	20	186	135	66	49	215	67	0	W	16.0	40	E
		B	43	253	4130	1768	454	335	3772	1164					

* A - Direction Frequency
* B - Mileage by Direction

TABLE II

"INSTANTANEOUS" HOURLY WIND VALUES

July 20 - 24, 1970

CFAV LAYMORE

DATE	TIME	WIND	
July, 1970	(PST)	Speed (knots)	Direction (True)
20	1800	05	E.S.E.
	1900	05	E.S.E.
	2000	light airs	-
	2100	05	S.W.
	2200	04	W
	2300	05	W
	2400	05	W
21	0100	18	W.N.W.
	0200	15	W
	0300	20	W.N.W.
	0400	18	W.N.W.
	0500	15	W.N.W.
	0600	15	W.N.W.
	0700	10	W.N.W.
	0800	10	W
	0900	10	W
	1000	08	W.N.W.
	1100	06	W.N.W.
	1200	06	W.N.W.
	1300	-	-
	1400	10	E
	1500	10	E
	1600	10	E
	1700	10	E
	1800	15	E
	1900	15	E
	2000	15	E
	2100	10	E.S.E.
	2200	08	E.S.E.
	2300	08	E.S.E.
	2400	05	E.S.E.
22	0100	02	E.S.E.
	0200	light airs	-
	0300	light airs	-
	0400	light airs	-
	0500	light airs	-
	0515	20	W.N.W.
	0600	18	W.N.W.
	0700	15	W.N.W.
	0800	12	W.N.W.
	0900	10	W.N.W.
	1000	08	W.N.W.
	1100	06	W.N.W.
	1200	05	W.N.W.

TABLE II (Continued)

"INSTANTANEOUS" HOURLY WIND VALUES

July 20 - 24, 1970

CFAV LAYMORE

DATE	TIME	WIND	
July, 1970	(PST)	Speed (knots)	Direction (True)
22	1300	light airs	-
	1400	light airs	-
	1500	02	E.S.E.
	1600	05	E.S.E.
	1700	05	E.S.E.
	1800	light airs	-
	1900	light airs	-
	2000	light airs	-
	2100	light airs	-
	2200	05	E
	2300	05	E
	2400	05	E
23	0100	05	E.S.E.
	0200	03	E.S.E.
	0300	10	E.S.E.
	0400	02	E.S.E.
	0500	light airs	-
	0600	light airs	-
	0700	10	E
	0800	light airs	-
	0900	08	S.E.
	1000	10	E.S.E.
	1100	12	S.E.
	1200	12	S.E.
	1300	10	S.E.
	1400	10	E.S.E.
	1500	10	E.S.E.
	1600	10	E.S.E.
	1700	light airs	-
	1800	light airs	-
	1900	light airs	-
	2000	light airs	-
	2100	light airs	-
	2200	08	W.N.W.
	2300	10	W.N.W.
	2400	12	W.N.W.
24	0100	15	W.N.W.
	0200	10	W.N.W.
	0300	10	W
	0400	23	W

TABLE II (Continued)

"INSTANTANEOUS" HOURLY WIND VALUES

July 20 - 24, 1970

CFAV LAYMORE

DATE	TIME	WIND	
July, 1970	(PST)	Speed (knots)	Direction (True)
24	0500	15	W
	0600	15	W
	0700	10	W
	0800	08	W
	0900	10	W.N.W.
	1000	10	W.N.W.
	1100	10	W.N.W.

TABLE III

"INSTANTANEOUS" HOURLY WIND VALUES

August 4 - 7, 1970

CSS VECTOR

DATE	TIME	WIND	
August, 1970	(PST)	Speed (knots)	Direction (True)
4	1600	15	S.E.
	1700	15	S.E.
	1800	15	S.E.
	1900	18	S.E.
	2000	22	S.E.
	2100	15	S.E.
	2200	23	S.E.
	2300	23	S.E.
	2400	16	S.E.
5	0100	14	S.E.
	0200	10	S.E.
	0300	08	S
	0400	05	S
	0500	05	S.E.
	0600	10	S.E.
	0700	12	S.E.
	0800	15	S.E.
	0900	23	S.E.
	1000	20	S.E.
	1100	15	S.E.
	1200	18	S.E.
	1300	18	S.E.
	1400	16	S.E.
	1500	14	S.E.
	1600	10	S.E.
	1700	05	S.E.
	1800	08	S.S.E.
	1900	10	S.E.
	2000	10	S.E.
	2100	02	E
	2200	light airs	-
	2300	light airs	-
	2400	light airs	-
6	0100	08	S.E.
	0200	12	S.E.
	0300	12	S.E.
	0400	15	S.E.

TABLE III (Continued)

"INSTANTANEOUS" HOURLY WIND VALUES

August 4 - 7, 1970

CSS VECTOR

DATE	TIME	WIND	
August, 1970	(PST)	Speed (knots)	Direction (True)
6	0500	10	S.E.
	0600	12	S.E.
	0700	10	S.E.
	0800	10	S.E.
	0900	20	S.E.
	1000	20	S.E.
	1100	20	S.E.
	1200	25	S.E.
	1300	25	E.S.E.
	1400	20	E.S.E.
	1500	18	E.S.E.
	1600	20	E.S.E.
	1700	18	E.S.E.
	1800	18	E.S.E.
	1900	10	S.E.
	2000	15	S
	2100	30	S
	2200	18	S
	2300	15	S
	2400	28	S
7	0100	15	E
	0200	18	E
	0300	15	E
	0400	11	E.S.E.
	0500	18	S.S.E.
	0600	14	S.E.
	0700	15	S.E.
	0800	15	S.E.
	0900	15	S.E.
	1000	15	S.E.
	1100	15	S.E.
	1200	18	S.E.
	1300	18	E.S.W.
	1400	22	E.S.E.

TABLE IV

"HOURLY" WIND VALUES

September 2 - 4, 1970

ENTRANCE ISLAND LIGHTSTATION

N.B. The values consist of the prevailing wind direction, and the total number of miles of wind, for each hour ending at the corresponding time noted. These data were obtained from unpublished meteorological records (Atmospheric Environment Service, Environment Canada, 1970).

DATE	TIME	WIND	
September, 1970	(PST)	Speed (knots)	Direction (True)
2	0700	6	S.E.
	0800	9	S.E.
	0900	14	S.E.
	1000	19	E
	1100	20	E
	1200	20	E
	1300	21	S.E.
	1400	20	S.E.
	1500	18	S.E.
	1600	19	S.E.
	1700	14	S.E.
	1800	19	S.E.
	1900	20	S.E.
	2000	17	S.E.
	2100	21	S.E.
	2200	22	S.E.
	2300	20	S.E.
	2400	20	S.E.
3	0100	21	S.E.
	0200	17	S.E.
	0300	16	E
	0400	14	E
	0500	12	E
	0600	12	S.E.
	0700	7	S.E.
	0800	9	S.W.
	0900	5	W

TABLE IV (Continued)

"HOURLY" WIND VALUES

September 2 - 4, 1970

ENTRANCE ISLAND LIGHTSTATION

DATE	TIME	WIND	
September, 1970	(PST)	Speed (knots)	Direction (True)
3	1000	10	S.W.
	1100	10	S.W.
	1200	7	S.W.
	1300	13	S.W.
	1400	15	S.W.
	1500	14	S.W.
	1600	13	S
	1700	12	S.W.
	1800	15	S.W.
	1900	10	S
	2000	7	S
	2100	5	S
	2200	7	S.W.
	2300	7	W
	2400	11	N.W.
4	0100	7	N.W.
	0200	6	W
	0300	10	W
	0400	10	N.W.
	0500	13	N.W.
	0600	17	N.W.
	0700	21	W
	0800	23	W
	0900	24	W
	1000	23	N.W.

TABLE V

"HOURLY" WIND VALUES RECORDED AT:

A. PROPOSED OUTFALL SITE (FRB INVESTIGATOR NO. 1)

B. ENTRANCE ISLAND LIGHTSTATION

September 8 - 11, 1970

N.B. The values from A are "instantaneous" ones, as in Tables II and III.
The values from B consist of the prevailing wind direction, and the total number of miles of wind, for each hour ending at the corresponding time noted; these latter data were obtained from unpublished meteorological records (Atmospheric Environment Service, Environment Canada, 1970).

DATE	TIME	A WIND		B WIND	
September 1970	(PST)	Speed (knots)	Direction (True)	Speed (knots)	Direction (True)
8	1500	8	W	7	N.W.
	1600	10	W	2	N.W.
	1700	Calm	-	4	W
	1800	Calm	-	3	S
	1900	Calm	-	4	S
	2000	Calm	-	2	E
	2100	Calm	-	5	E
	2200	Calm	-	3	S.E.
	2300	Calm	-	3	S.E.
	2400	Calm	-	4	S.E.
9	0100	8	W	6	W
	0200	12	W	3	W
	0300	10	W	4	W
	0400	10	W	9	W
	0500	8	W	9	W
	0600	12	W	9	W
	0700	11	W	14	W
	0800	15	W	15	W
	0900	15	W	17	N.W.
	1000	15	W.S.W.	16	N.W.
	1100	18	W	15	N.W.
	1200	-	-	15	N.W.

TABLE V (Continued)

"HOURLY" WIND VALUES RECORDED AT:

A. PROPOSED OUTFALL SITE (FRB INVESTIGATOR NO. 1)

B. ENTRANCE ISLAND LIGHTSTATION

September 8 - 11, 1970

DATE	TIME	A		B	
		WIND		WIND	
September 1970	(PST)	Speed (knots)	Direction (True)	Speed (knots)	Direction (True)
9	1300	16	W	14	N.W.
	1400	16	W	13	N.W.
	1500	16	W.N.W.	14	N.W.
	1600	14	W.N.W.	16	N.W.
	1700	14	W.N.W.	17	N.W.
	1800	18	W.N.W.	17	N.W.
	1900	12	W	17	N.W.
	2000	11	W	19	N.W.
	2100	17	W	17	W
	2200	24	W.N.W.	18	W
	2300	21	W.N.W.	24	N.W.
	2400	20	W.N.W.	19	W
10	0100	24	W	22	N.W.
	0200	26	W	25	W
	0300	26	W	26	N.W.
	0400	20	W	26	N.W.
	0500	13	W	23	N.W.
	0600	22	W.N.W.	25	N.W.
	0700	20	W.N.W.	25	N.W.
	0800	23	W	22	N.W.
	0900	18	W	23	N.W.
	1000	24	W	21	N.W.
	1100	18	W	23	N.W.
	1200	18	W	21	N.W.
	1300	20	W	23	N.W.
	1400	22	W	21	N.W.
	1500	18	N.W.	24	W

TABLE V (Continued)

"HOURLY" WIND VALUES RECORDED AT:

A. PROPOSED OUTFALL SITE (FRB INVESTIGATOR NO. 1)

B. ENTRANCE ISLAND LIGHTSTATION

September 8 - 11, 1970

		A		B	
DATE	TIME	WIND		WIND	
September 1970	(PST)	Speed (knots)	Direction (True)	Speed (knots)	Direction (True)
10	1600	20	N.W.	24	W
	1700	-	-	22	W
	1800	27	N.W.	23	W
	1900	36	N.W.	29	W
11	0800	-	-	17	W
	0900	16	W	20	N.W.
	1000	18	W	19	N.W.
	1100	18	W	19	N.W.
	1200	16	W	19	N.W.
	1300	15	W	18	N.W.
	1400	18	W	19	N.W.
	1500	16	W	20	W

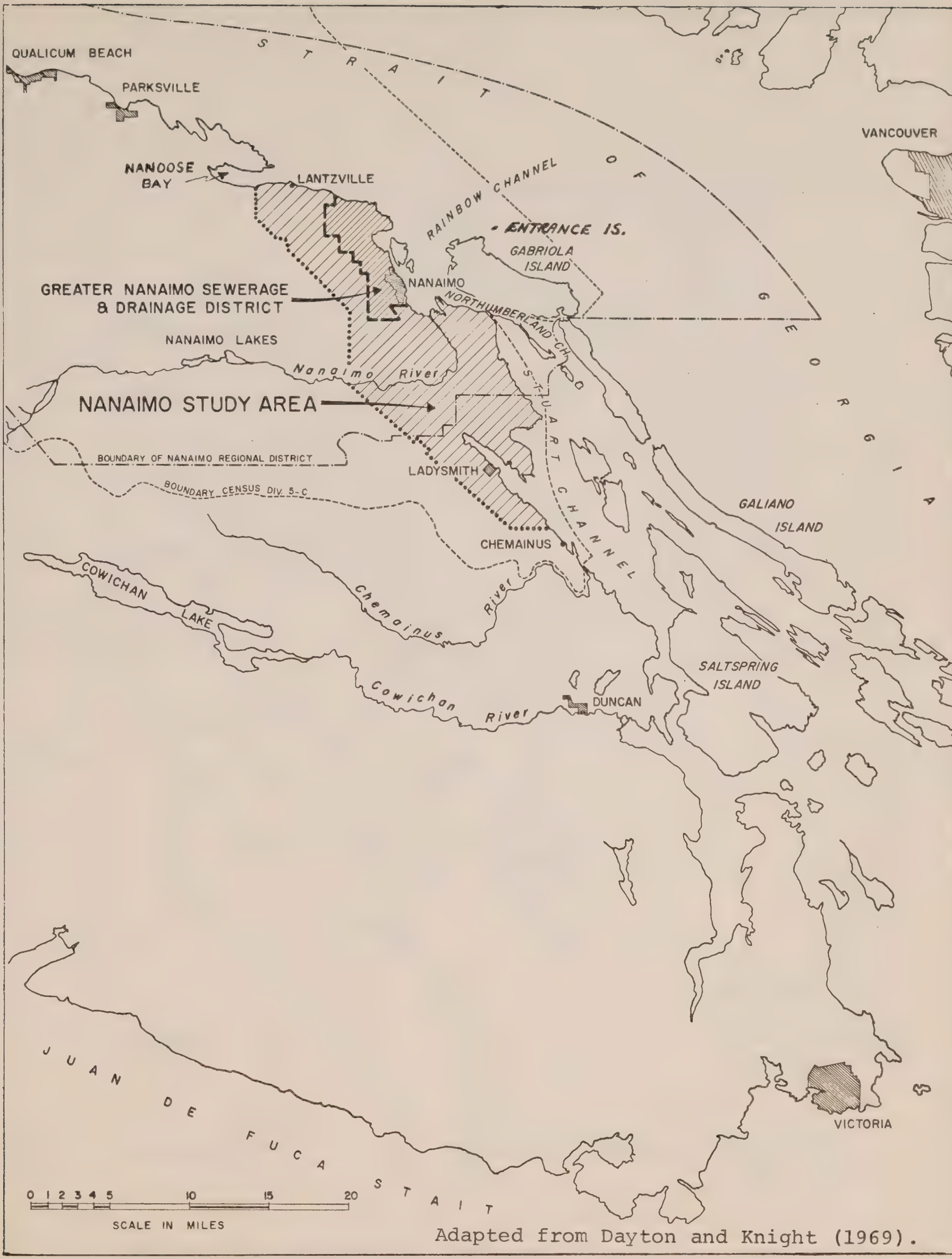


Figure 1. Greater Nanaimo Sewerage and Drainage District (GNSDD).

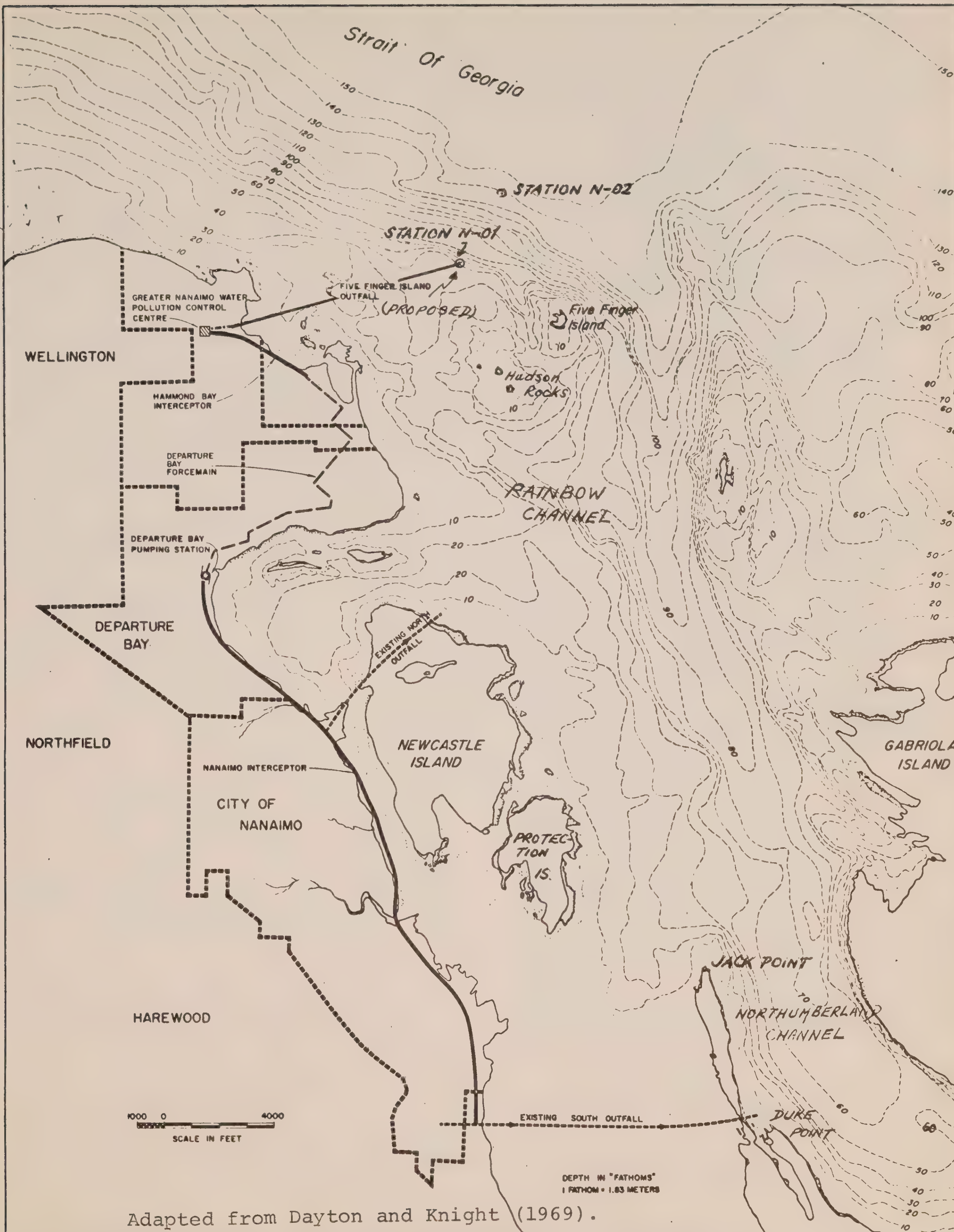
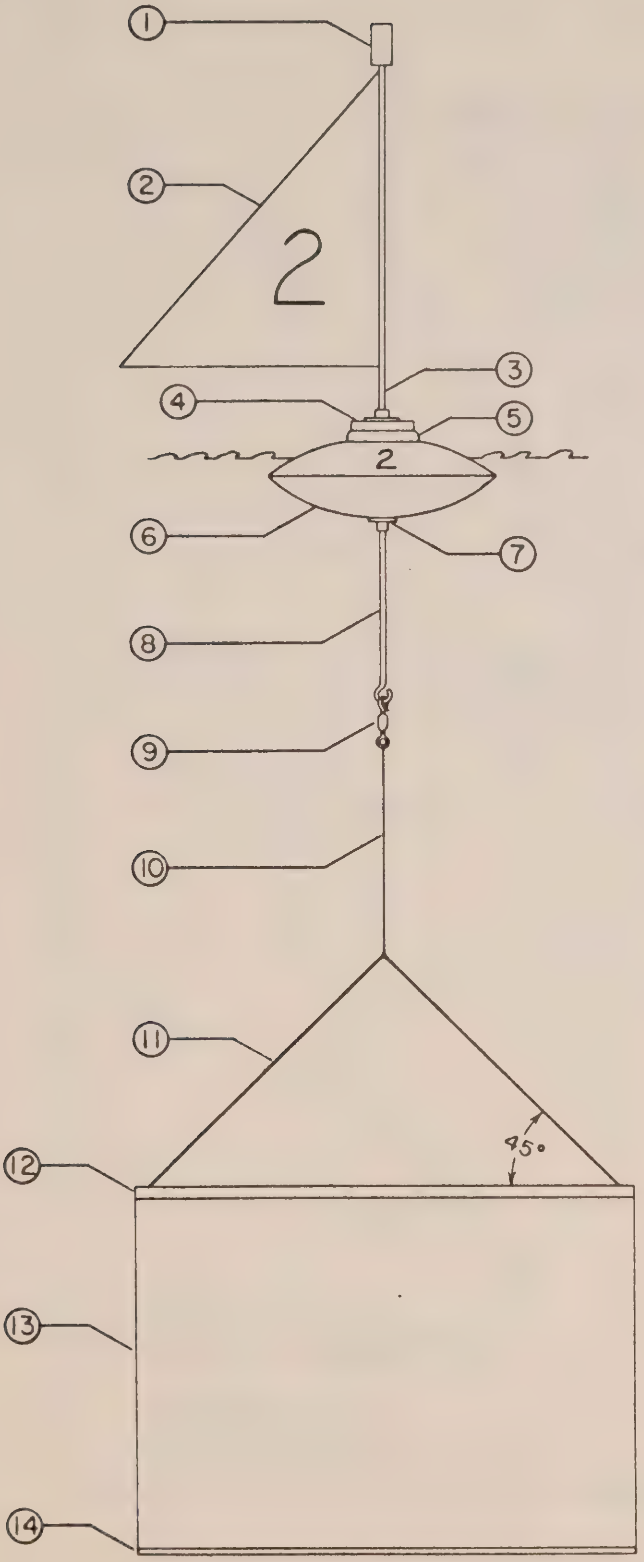


Figure 2. Location of proposed GNSDD effluent outfall.



(1) Clear Ampak vial size AS9 with:
coloured film liner,
#5 rubber stopper,
G.E. 407, 4·9v flasher bulb
and socket.

(2) 24 in. 2 mil, fluorescent orange, polyethylene flag

(3) 38 in. lg. 3/16 in diam. stainless-steel rod, threaded 10-24 both ends

(4) Lid fittings

(5) 4 in. wide mouth polyethylene jar with:
polypropylene lid
Eveready No. 2774N, 6v. battery,
3·3 ohm series resistor.

(6) Polyurethane float

(7) 1 in. diam. wooden washer and steel collar with setscrew.

(8) 14 in. lg. 1/4 in. diam. stainless-steel rod with 1 in diam. eye one end and 1/4 N.F thread other end.

(9) Small swivel snap.

(10) 50 lb. test nylon monofilament

(11) Nylon monofilament bridle

(12) 8 ft. lg. cedar 1x2 S4S

(13) 8 ft. x 6 ft. 4 mil polyethylene

(14) 8 ft. lg. 5/8 in. diam. reinforcing iron

Figure 3. Free-floating current follower employed.

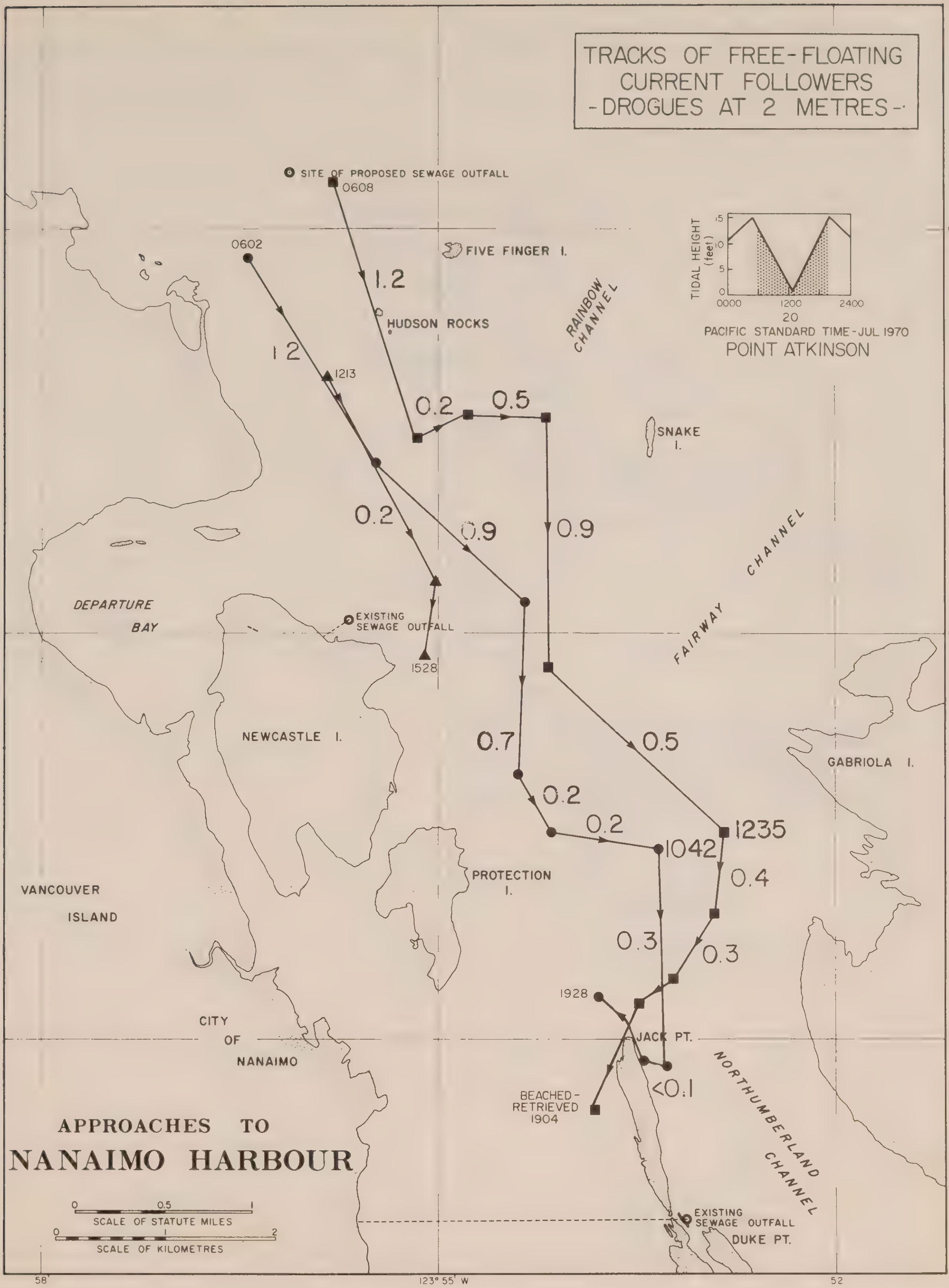


Figure 4. Results of "inshore" tracking session: 2 m follower. 20 July 1970.

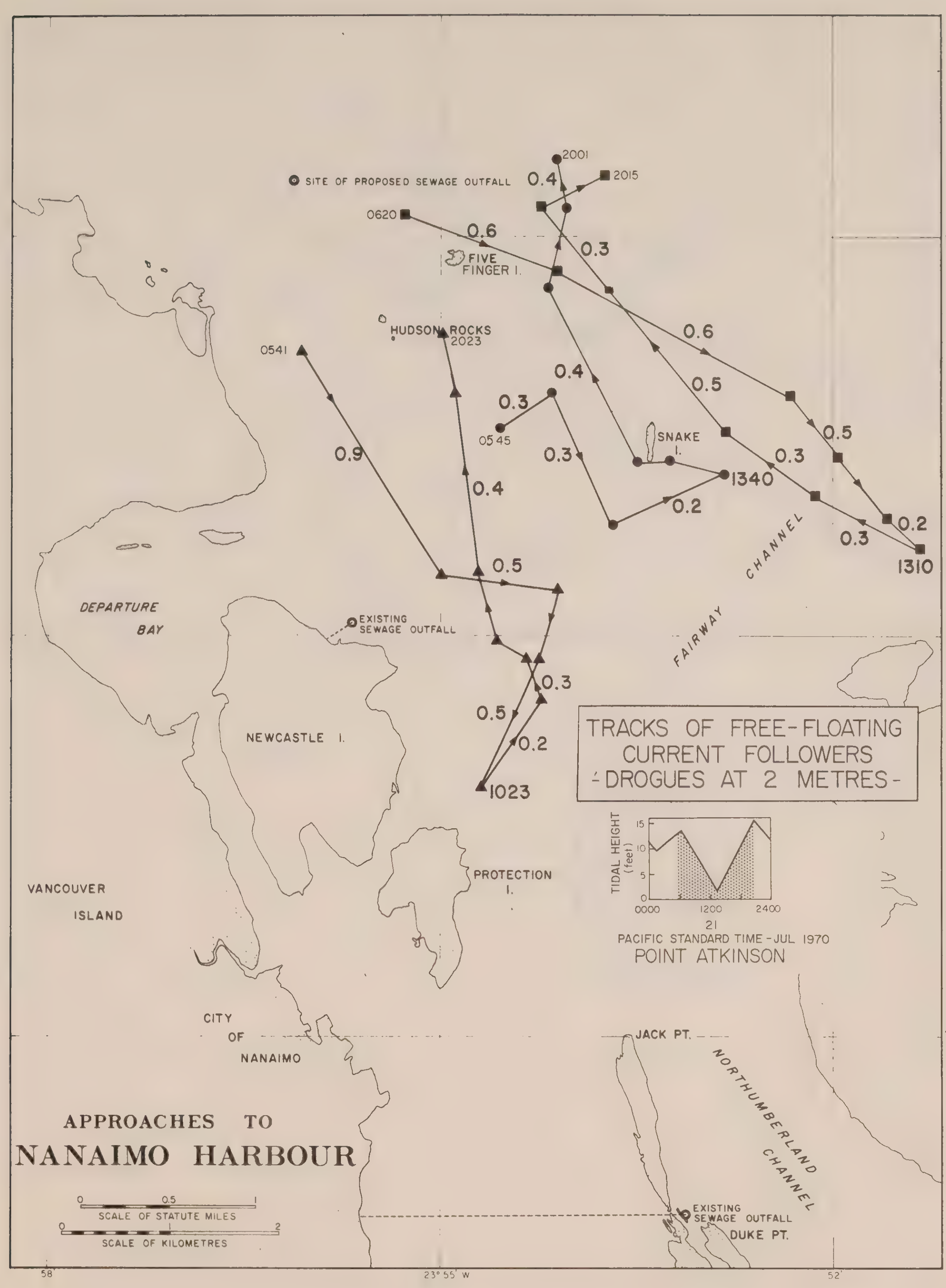


Figure 5. Results of "inshore" tracking session: 2 m follower. 21 July 1970.

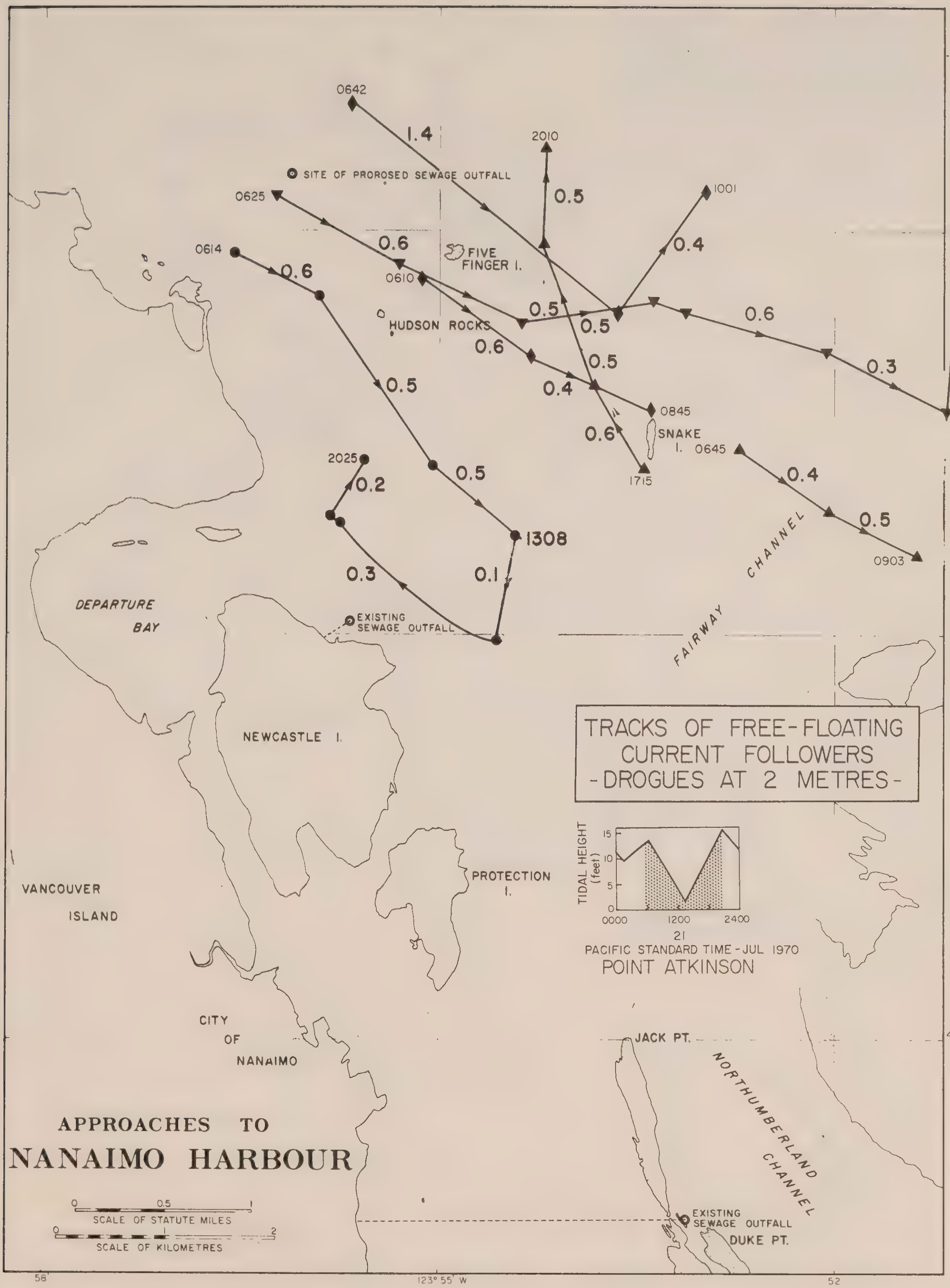


Figure 6. Results of "inshore" tracking session: 2 m follower. 21 July 1970.

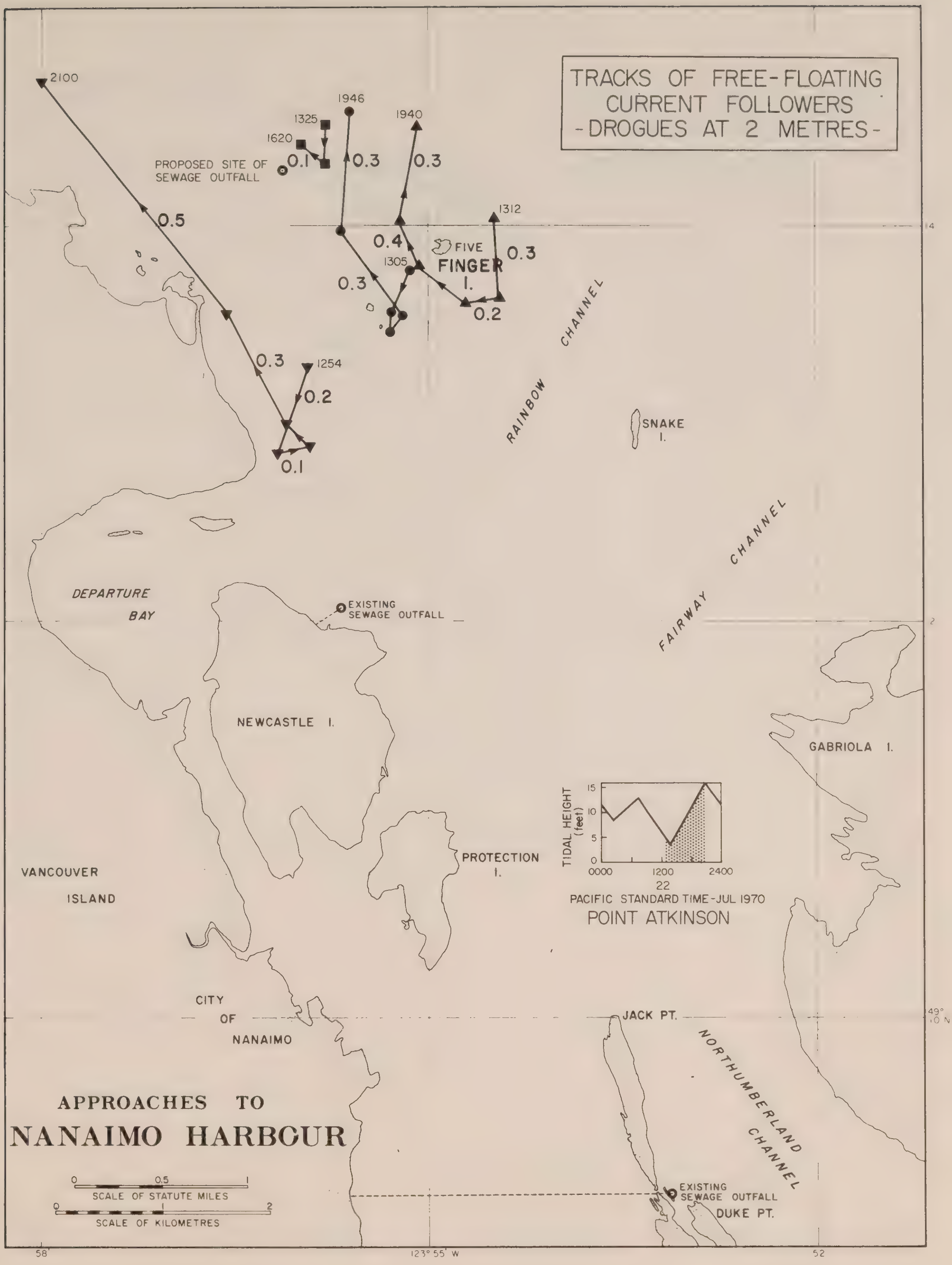


Figure 7. Results of "inshore" tracking session: 2 m follower. 22 July, 1970.

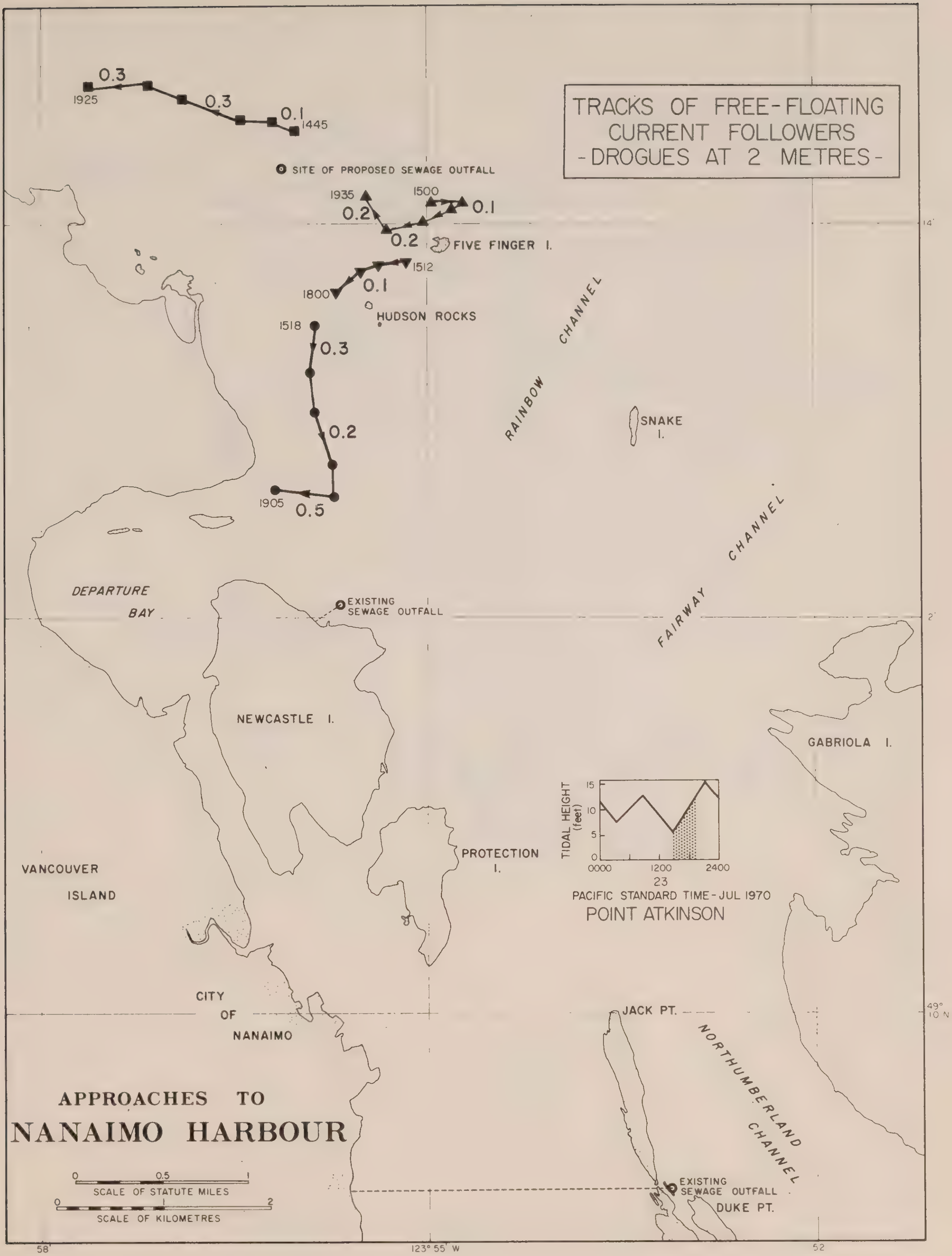


Figure 8. Results of "inshore" tracking session: 2 m follower. 23 July 1970.

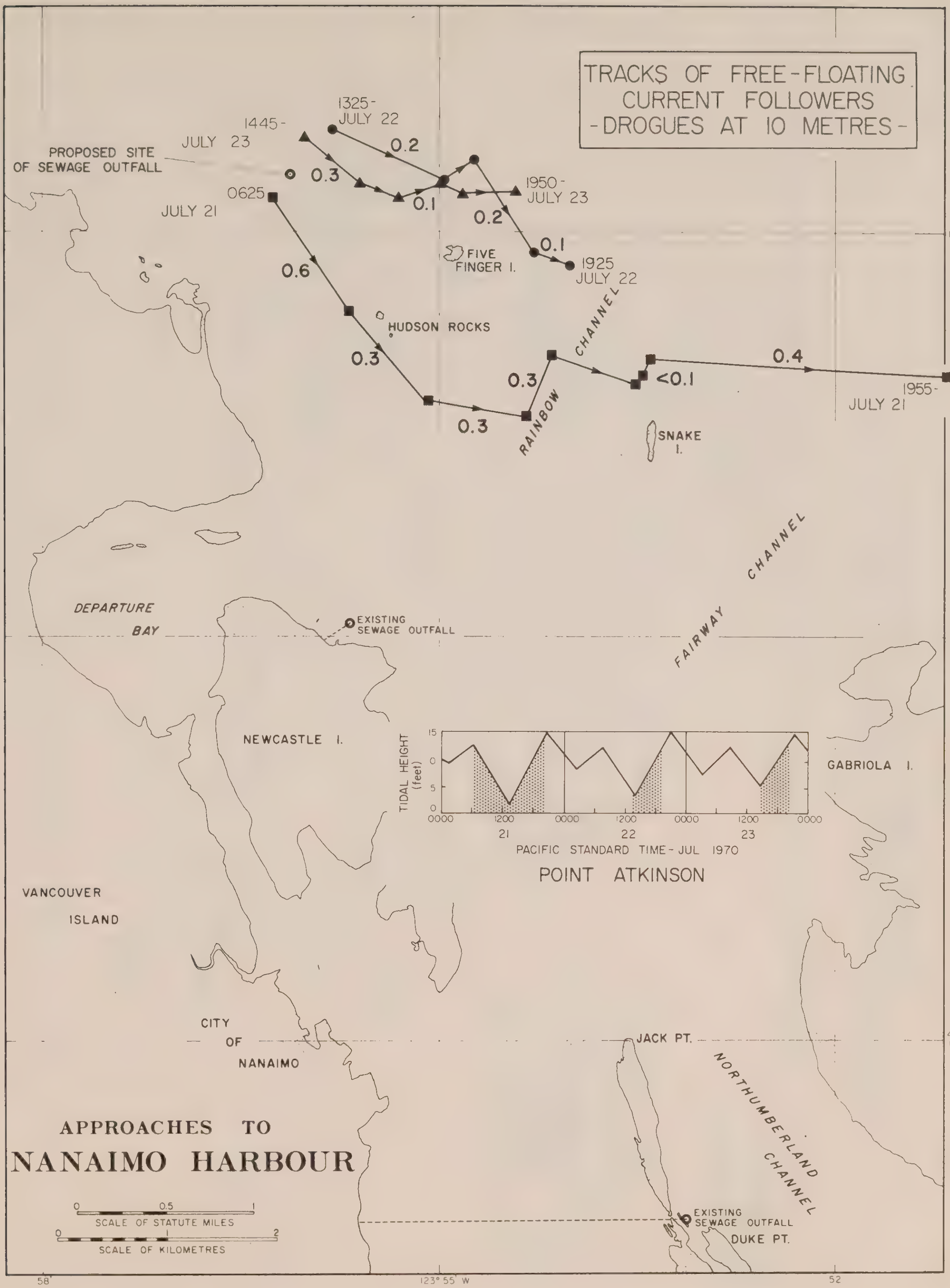


Figure 9. Results of "inshore" tracking session: 10 m follower. 21, 22 and 23 July 1970.

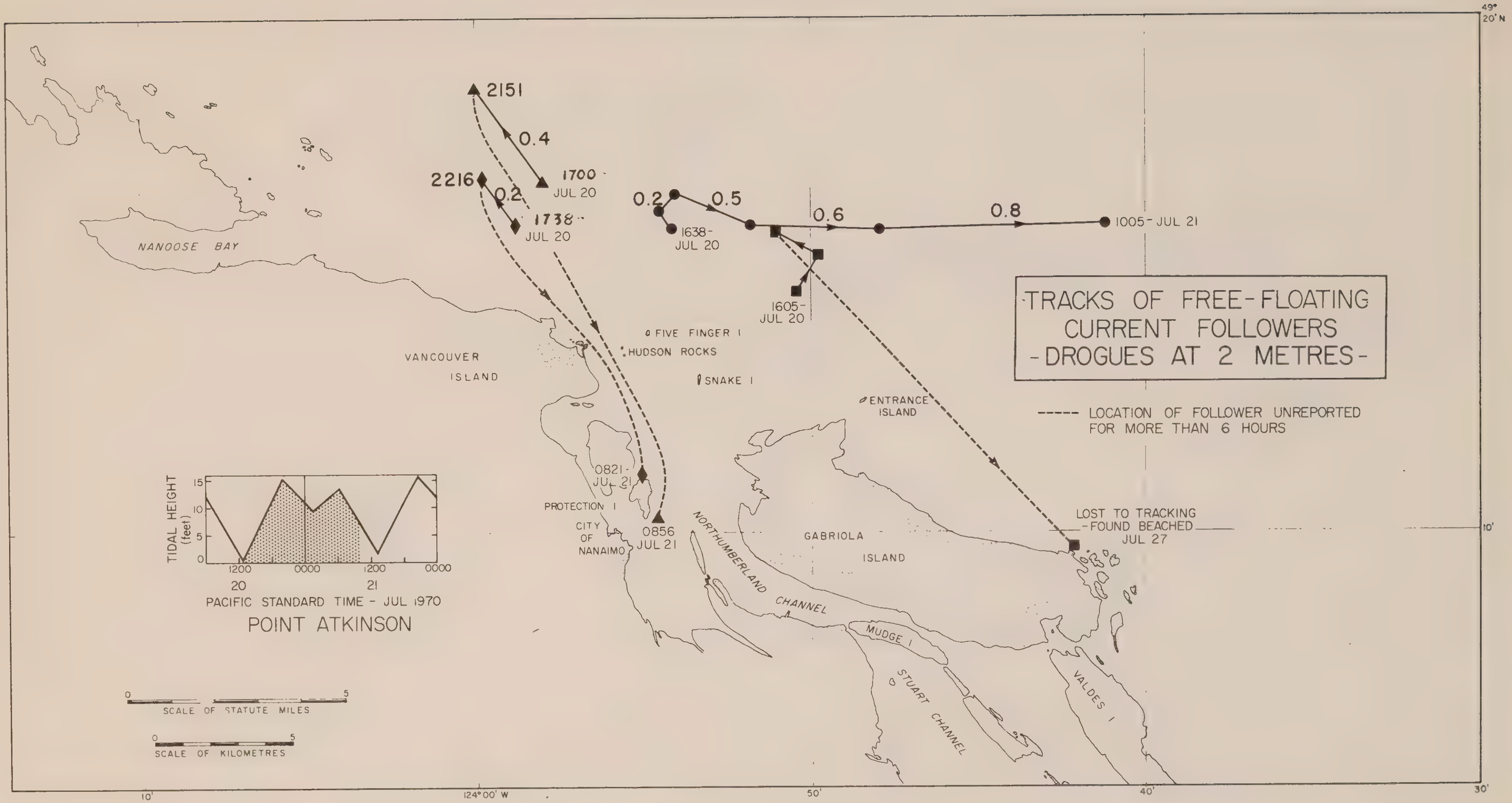


Figure 10. Results of "offshore" tracking session: 2 m follower. 20-21 July 1970.

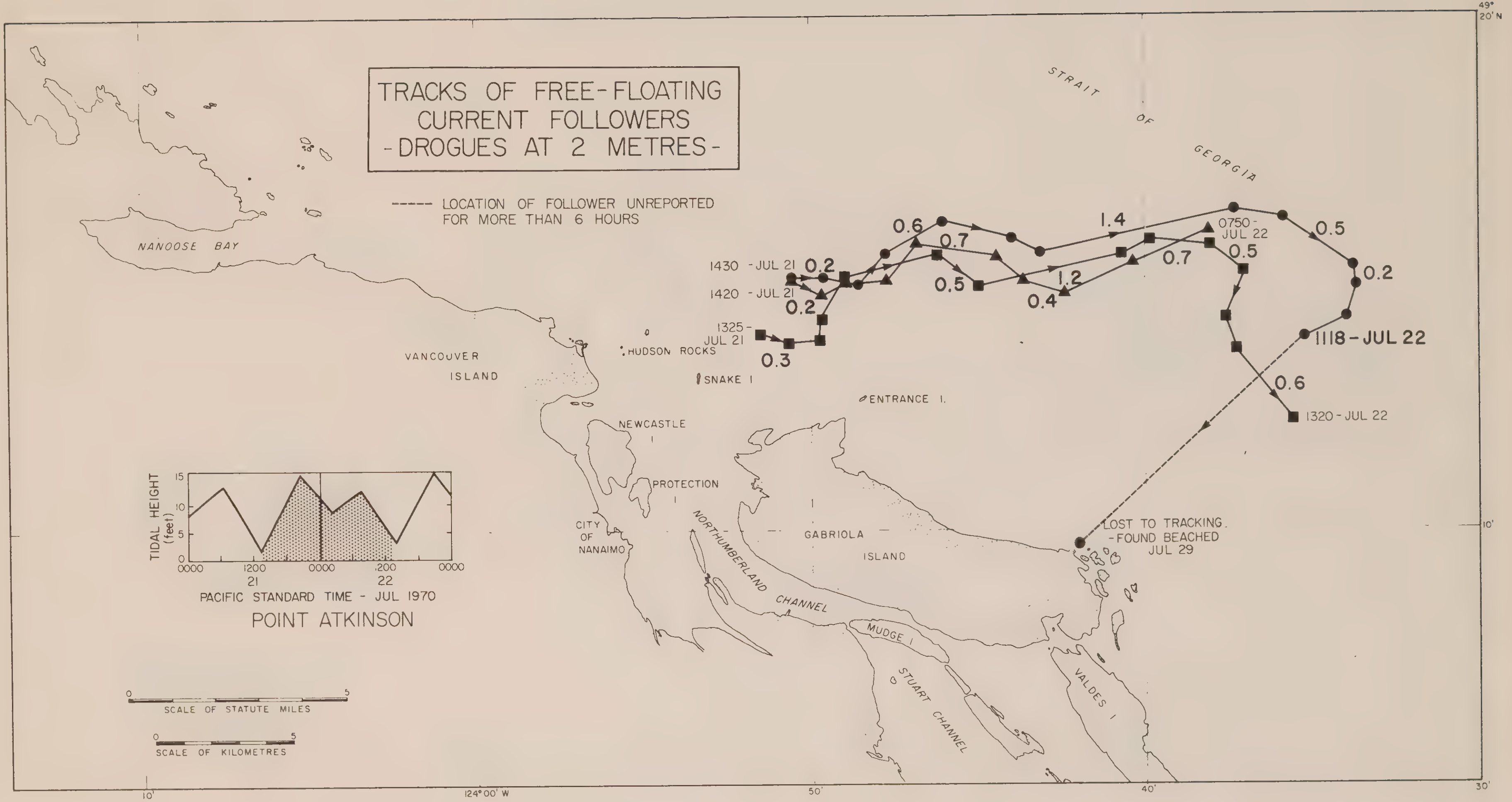


Figure 11. Results of "offshore" tracking session: 2 m follower. 21-22 July 1970.

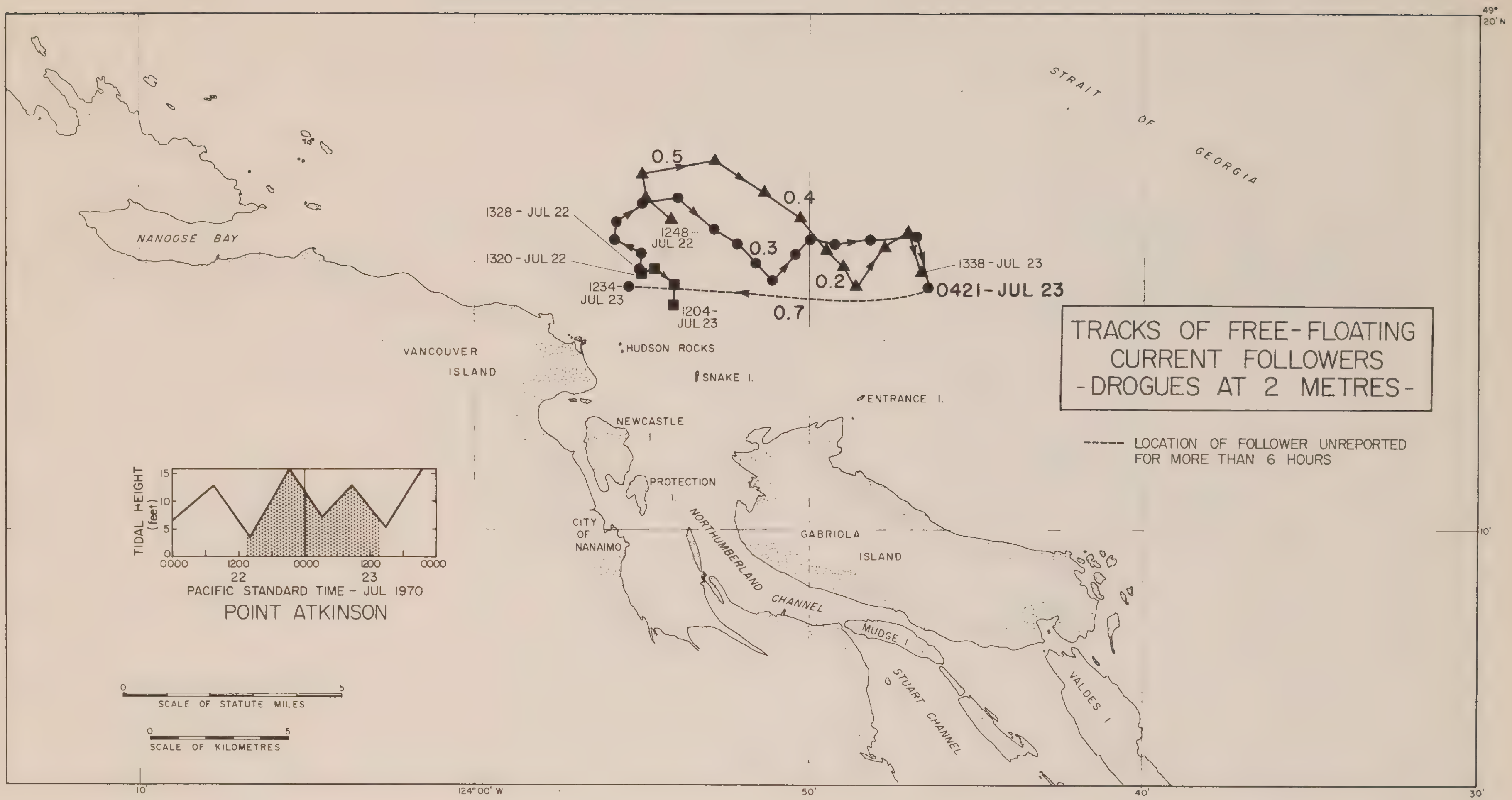


Figure 12. Results of "offshore" tracking session: 2 m followers. 22-23 July 1970.

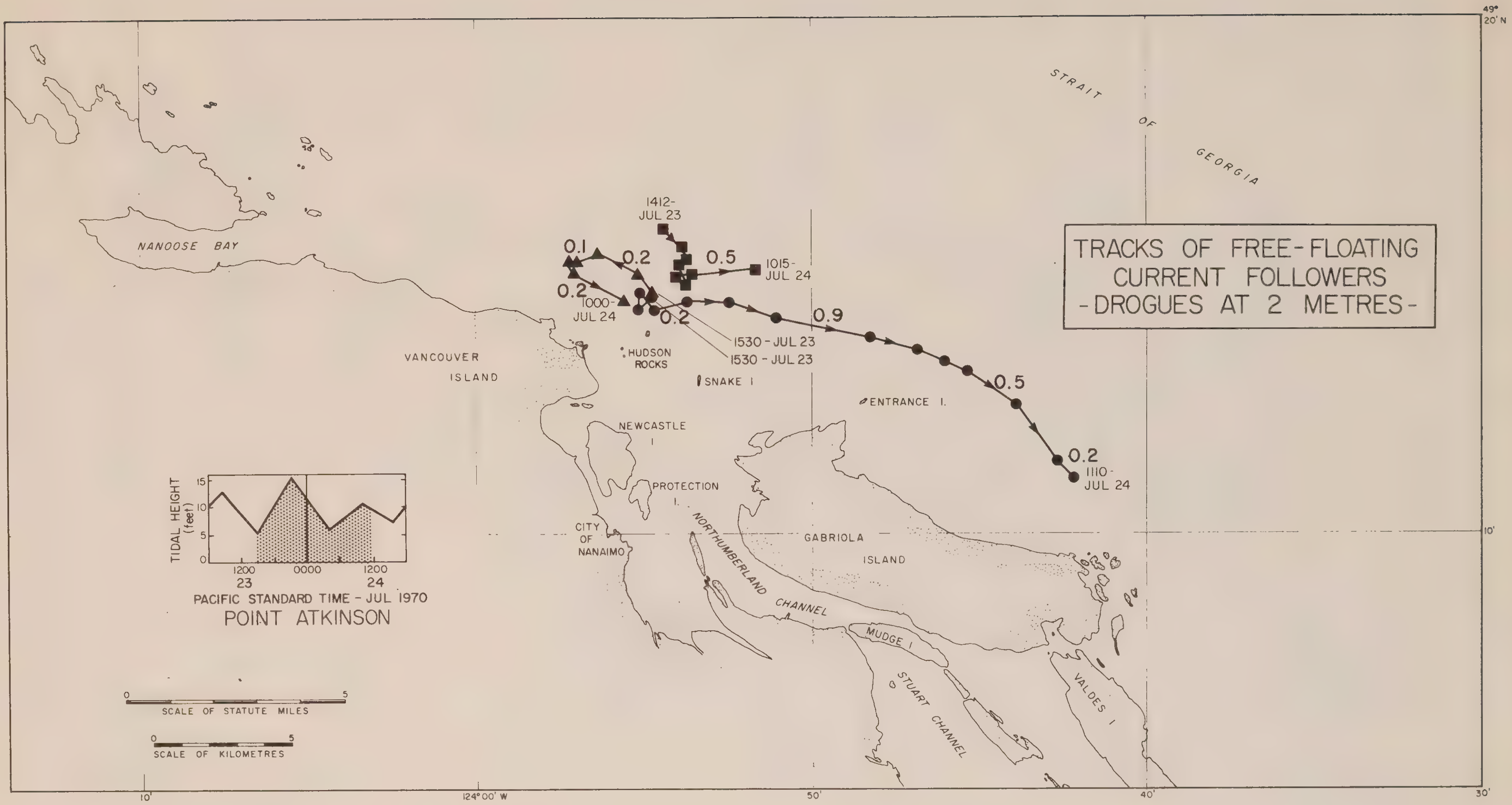


Figure 13. Results of "offshore" tracking session:
2 m followers. 23-24 July 1970.

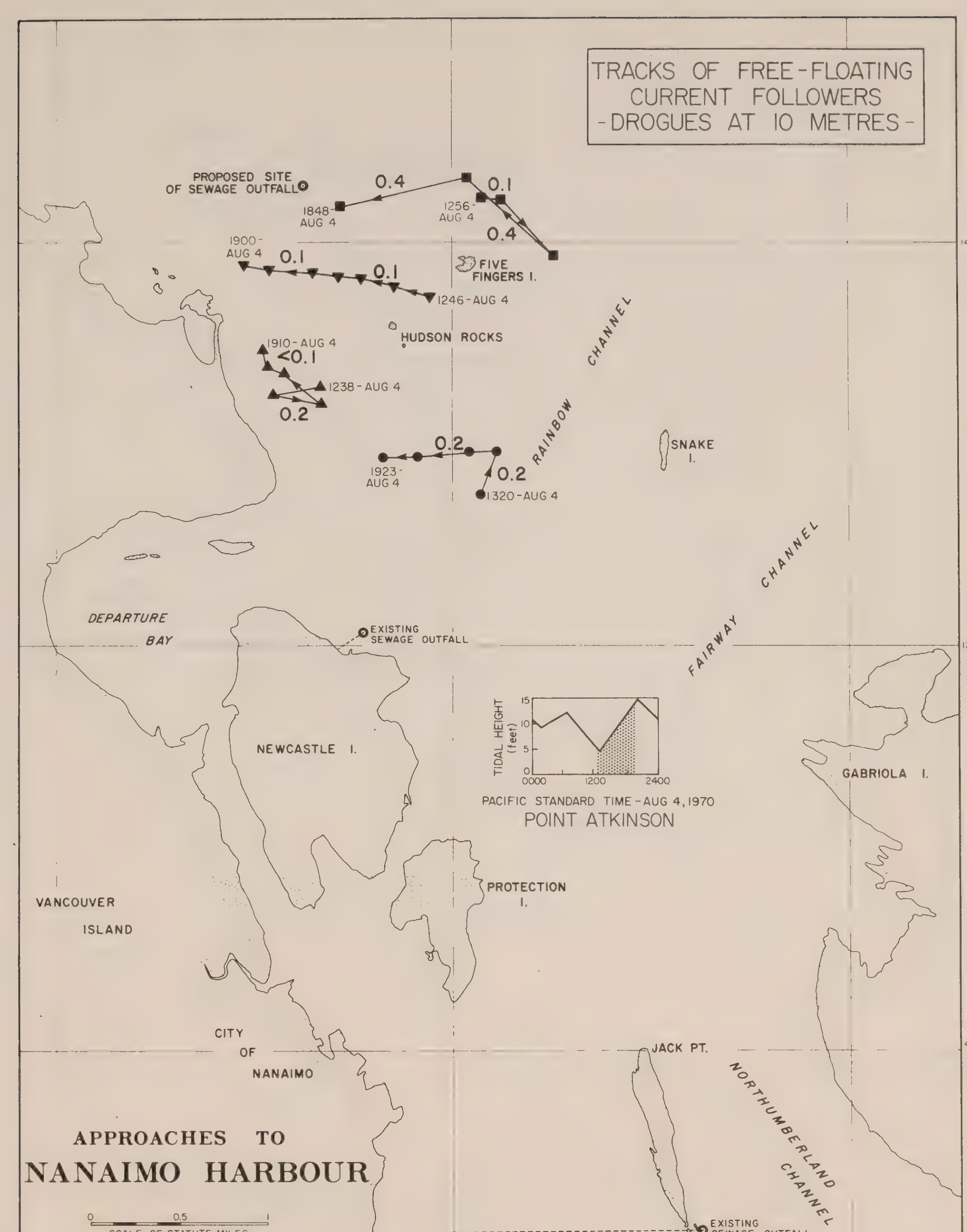


Figure 14. Results of "inshore" tracking session: 10 m follower. 4 August 1970.

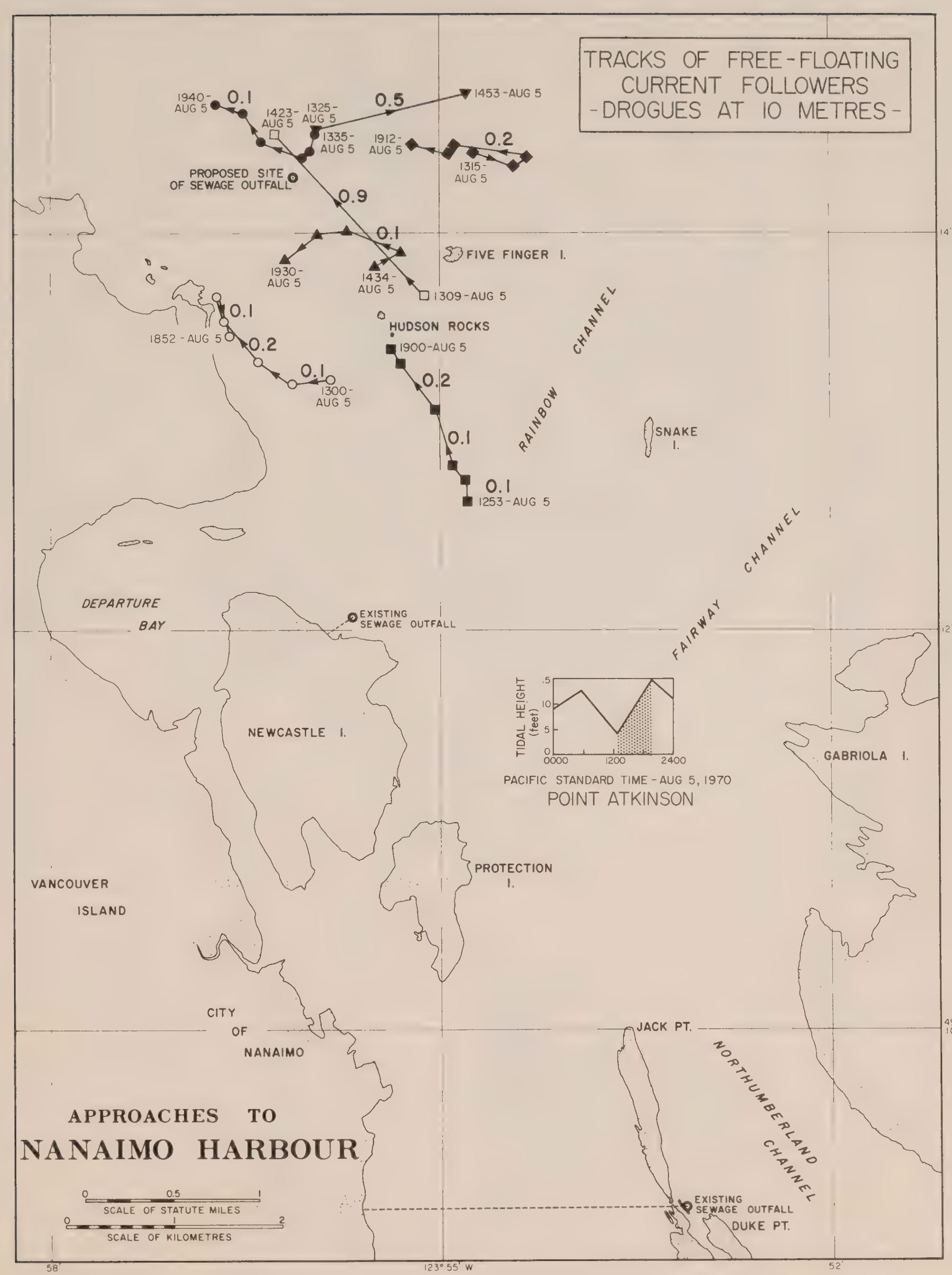


Figure 15. Results of "inshore" tracking session: 10 m follower. 5 August 1970.

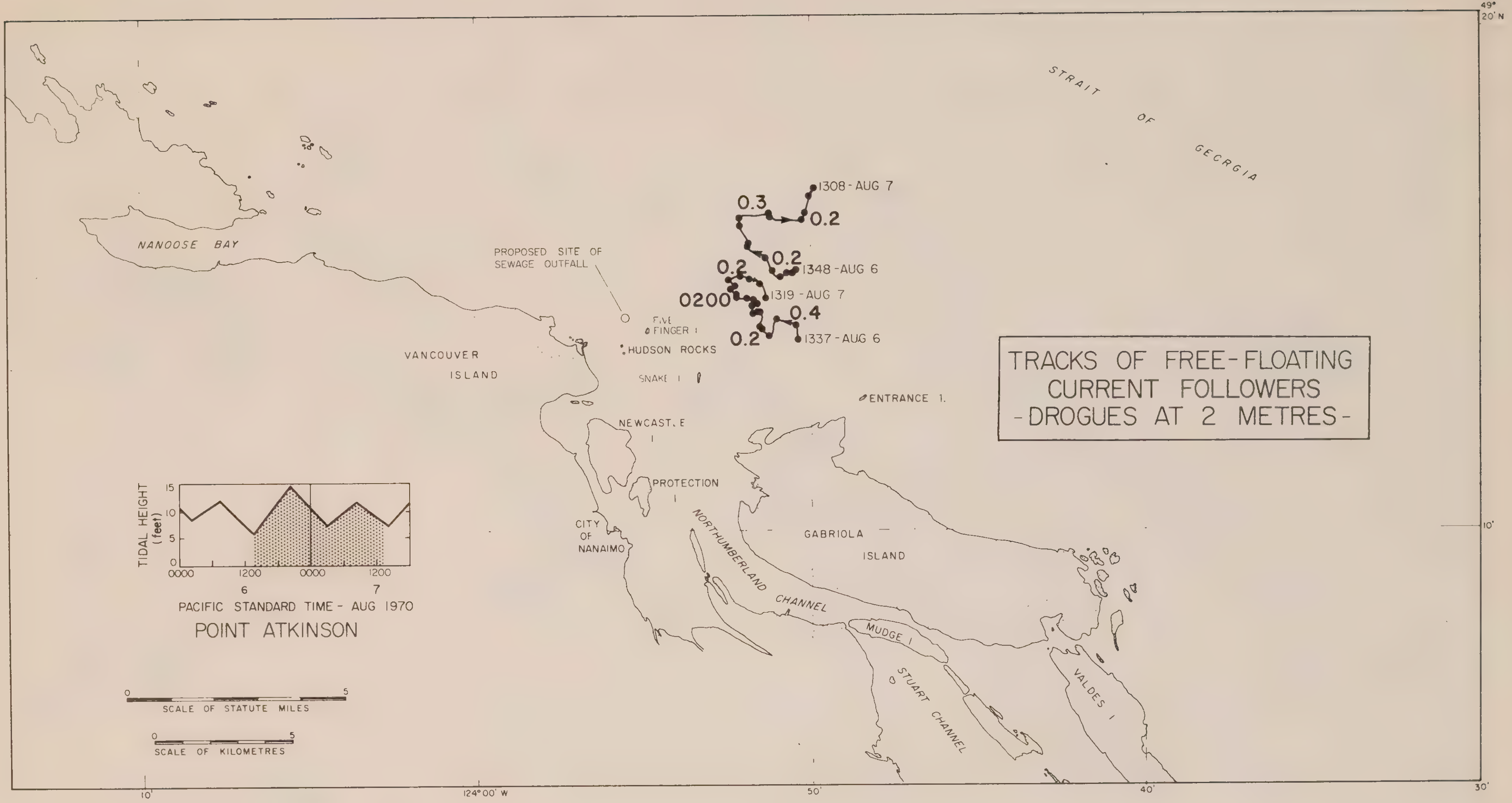


Figure 16. Results of "offshore" tracking session: 2 m follower. 6-7 August, 1970.

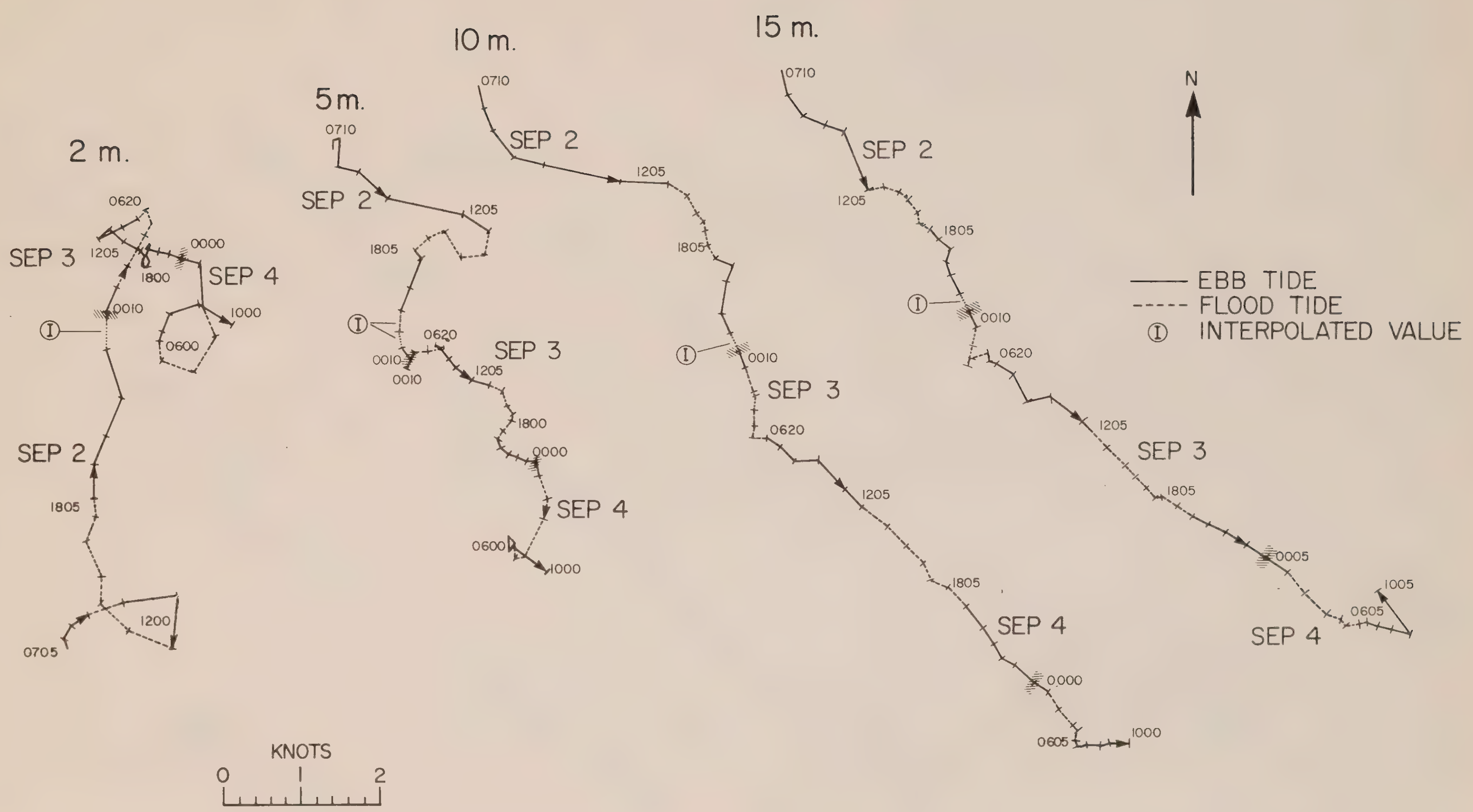


Figure 17. Progressive-vector diagrams for currents at 2, 5, 10 and 15 m depth at proposed outfall site: 2-4 September 1970.

Figure 18. Progressive-vector diagrams for currents at 20, 25, 30 and 35 m depth at proposed outfall site: 2-4 September 1970.

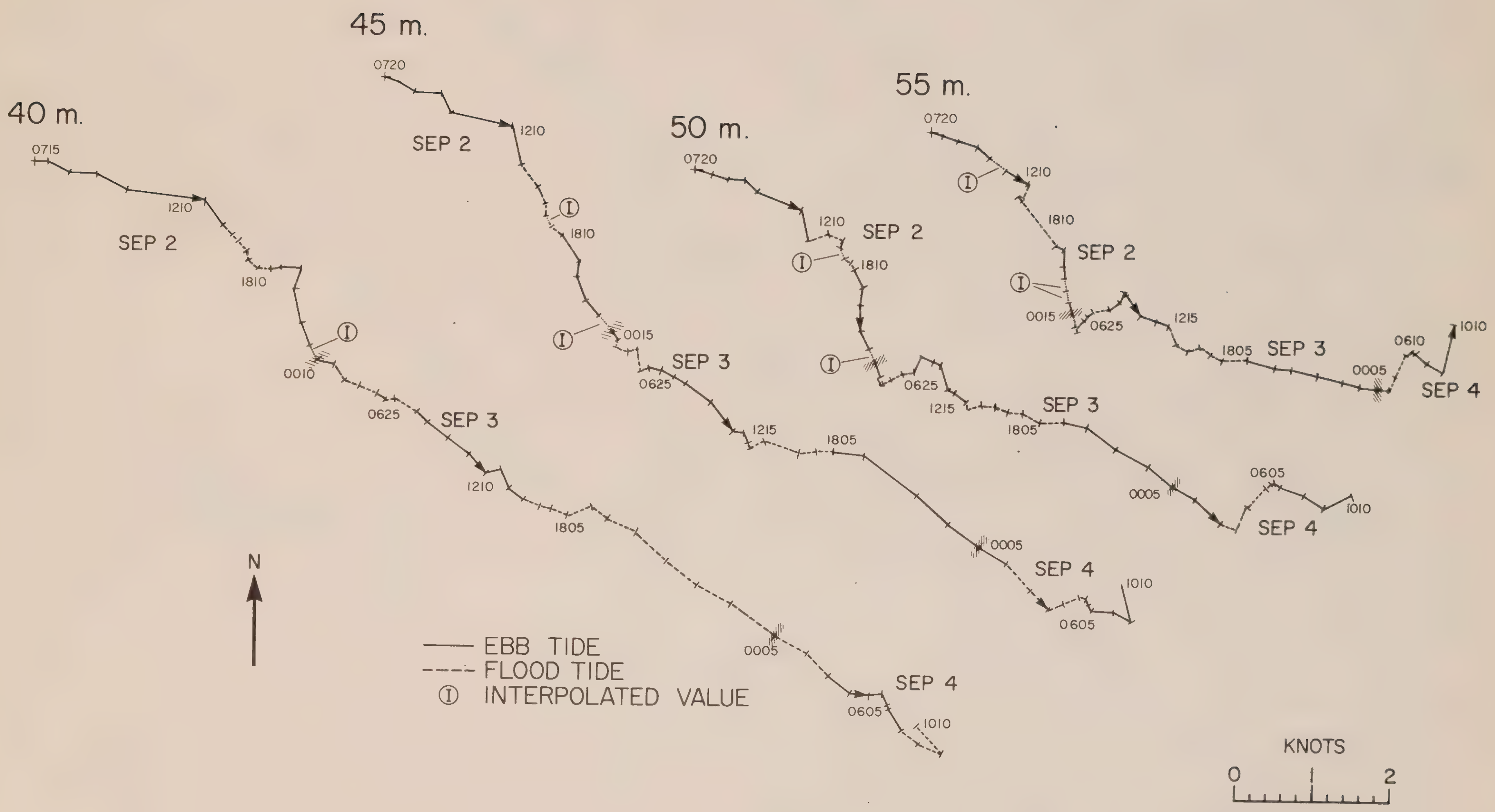


Figure 19. Progressive-vector diagrams for currents at 40, 45, 50 and 55 m depth at proposed outfall site: 2-4 September 1970.

Figure 20. Progressive-vector diagram for currents at 2, 5, 10 and 15 m depth at proposed outfall site: 8-11 September 1970.

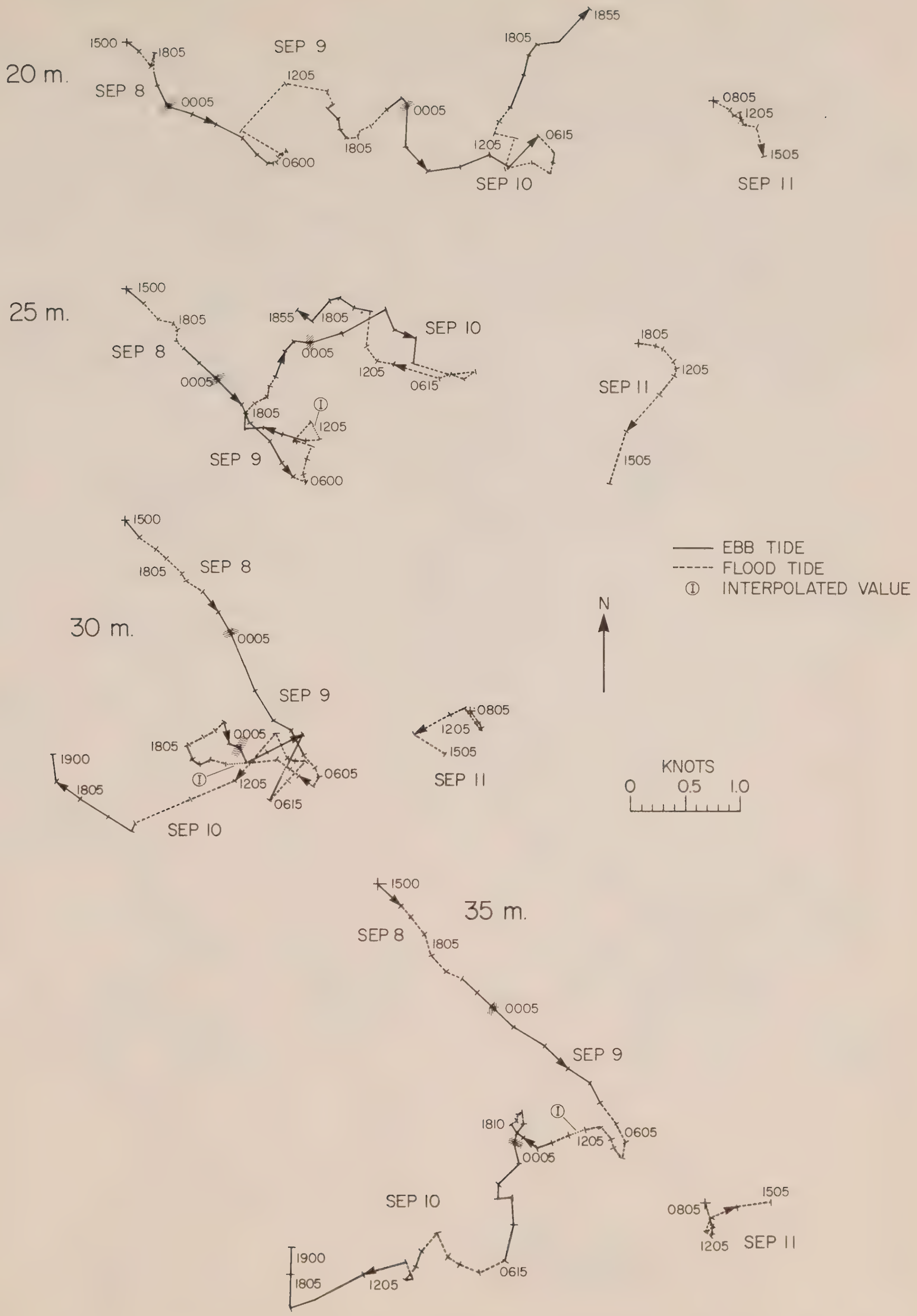


Figure 21. Progressive-vector diagrams for currents at 20, 25, 30 and 35 m depth at proposed outfall site: 8-11 September 1970.

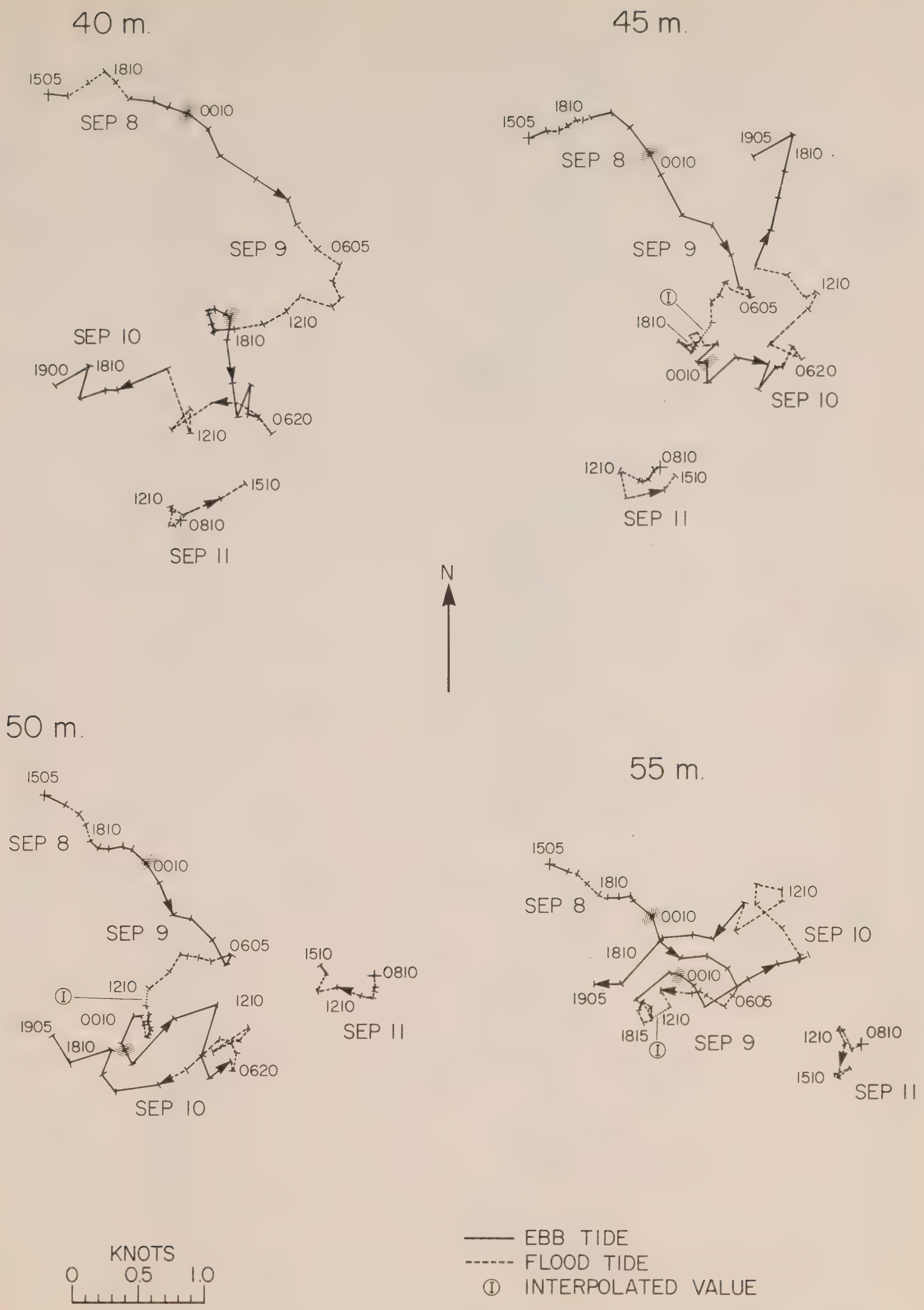


Figure 22. Progressive-vector diagrams for currents at 40, 45, 50 and 55 m depth at proposed outfall site: 8-11 September 1970.

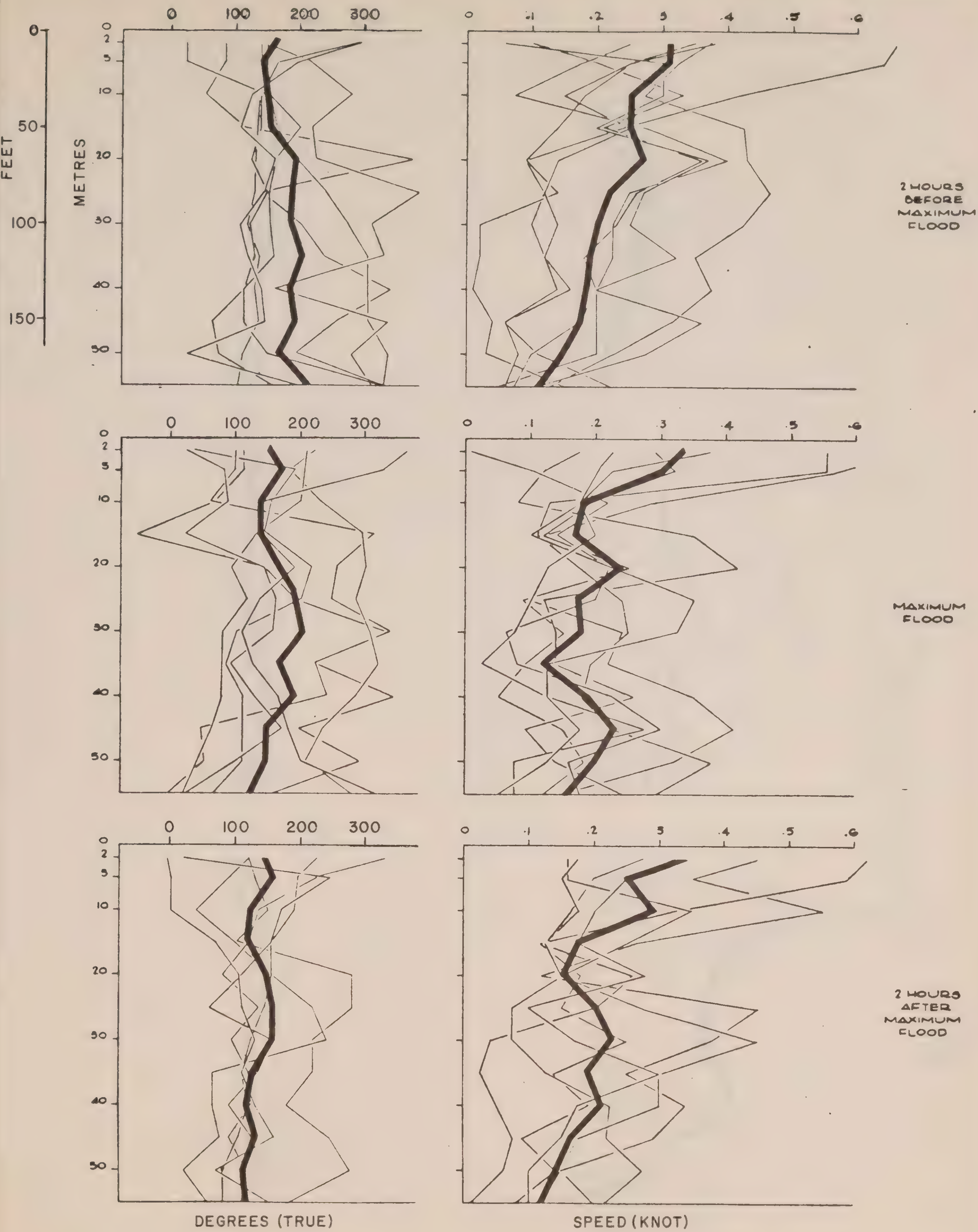


Figure 23. Speed and direction profiles at proposed outfall site: On flood tides.

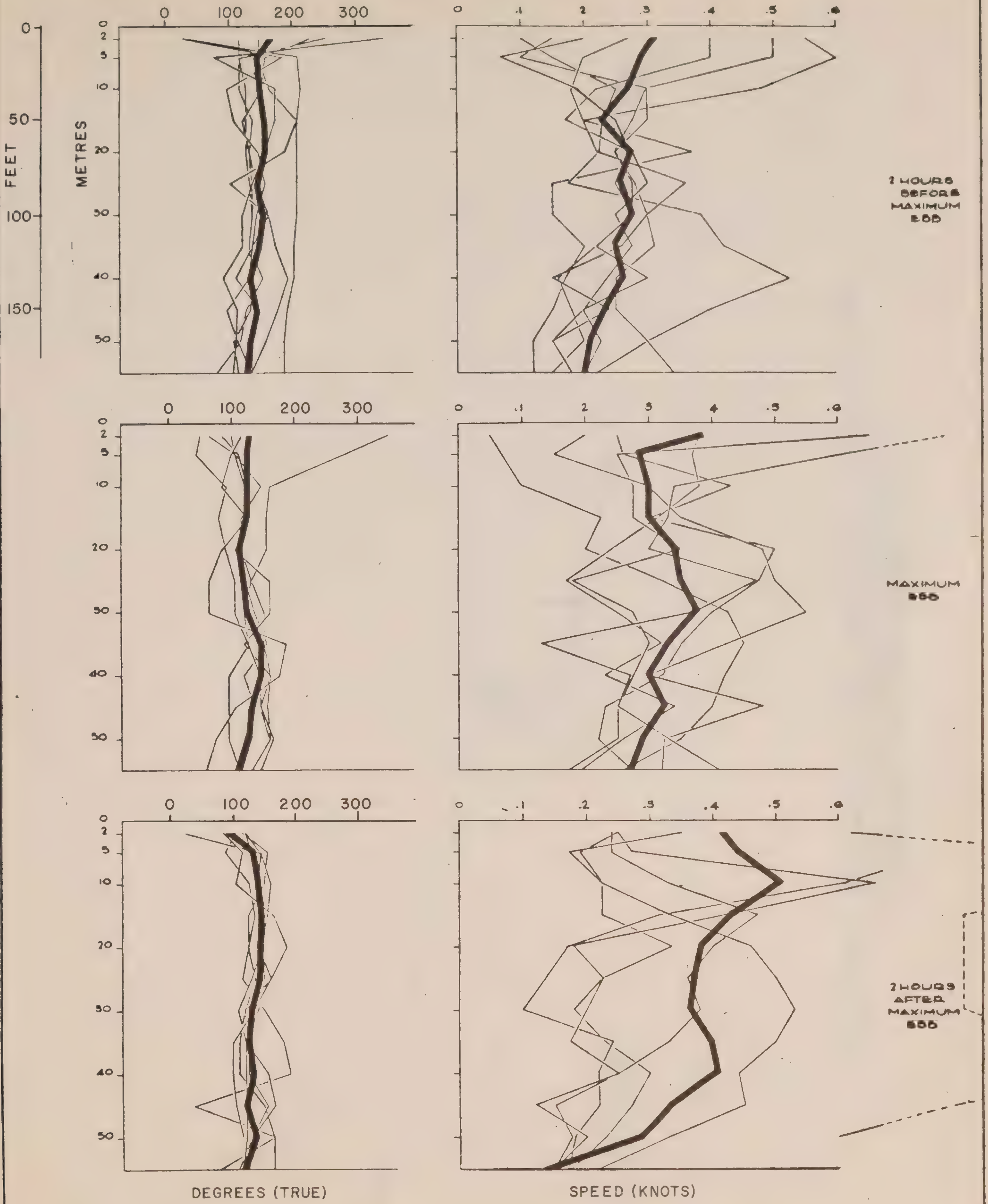


Figure 24. Speed and direction profiles at proposed outfall site: On ebb tides.

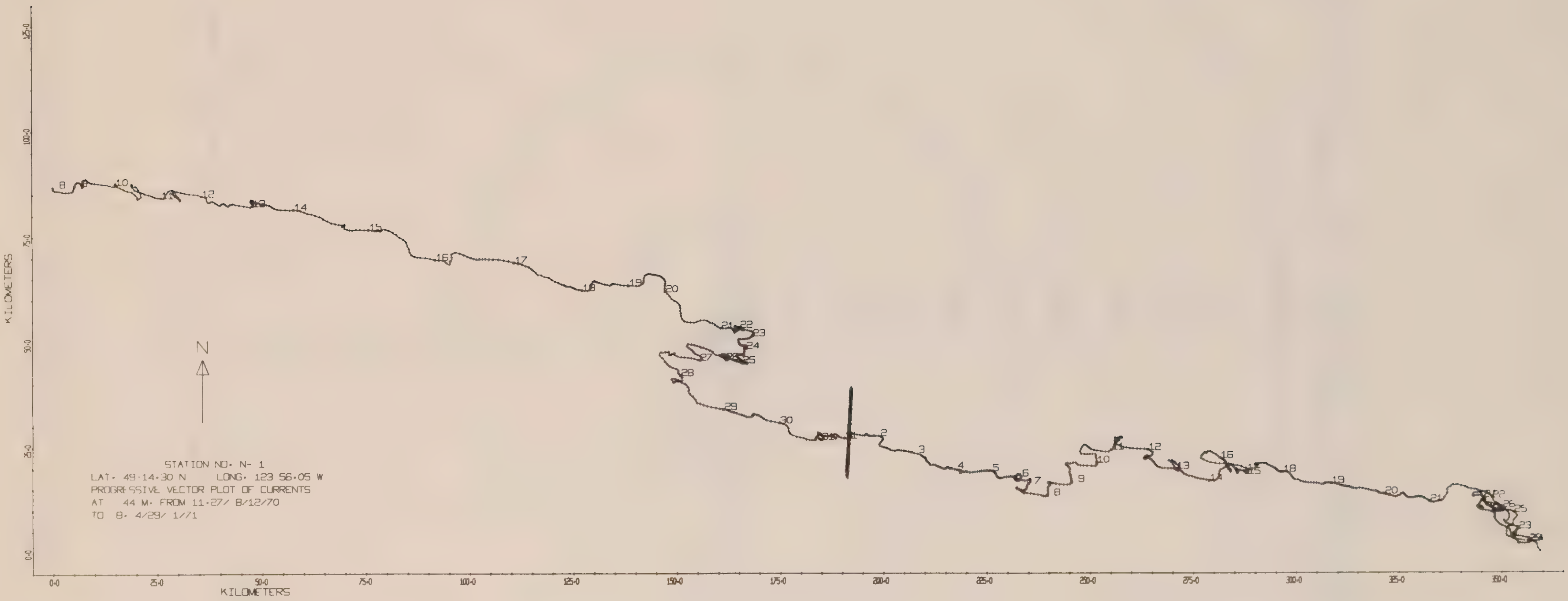


Figure 25a. Progressive-vector diagram for currents at 44 m depth at N-01 (proposed outfall site). 8 December 1970 - 29 January 1971.

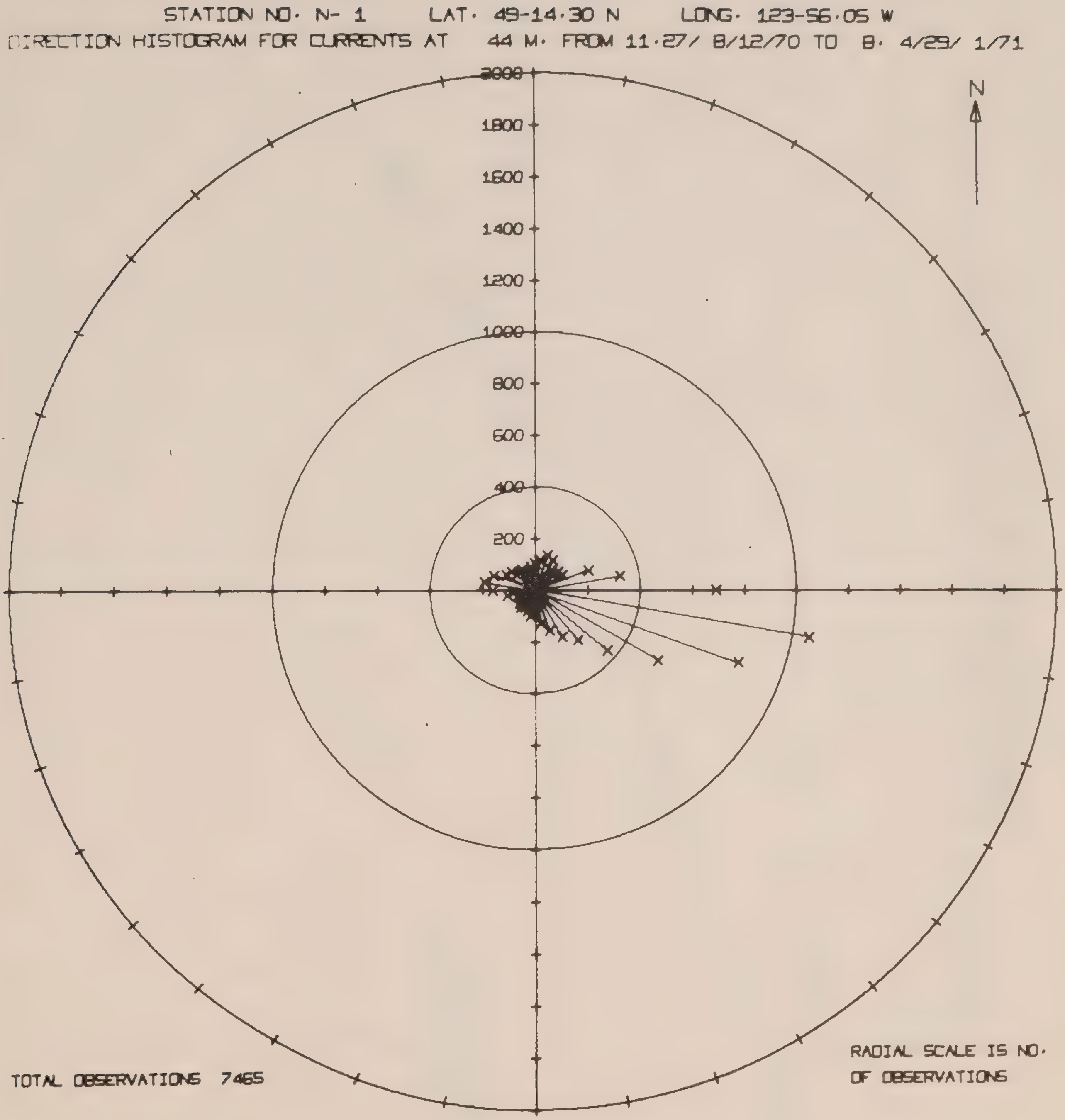


Figure 25b. Direction histogram for currents of Figure 25a.

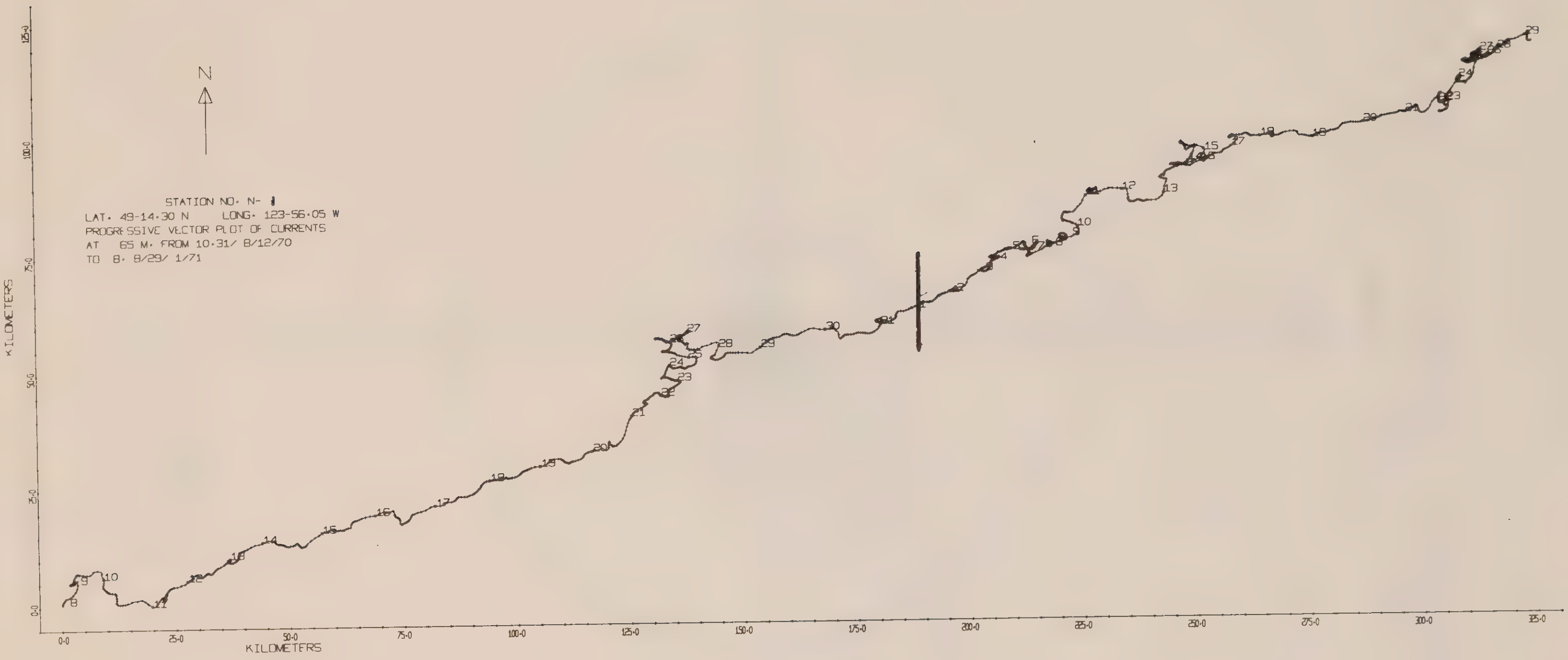


Figure 26a. Progressive-vector diagram for currents at 65 m depth at N-01 (proposed outfall site). 8 December 1970 - 29 January 1971.

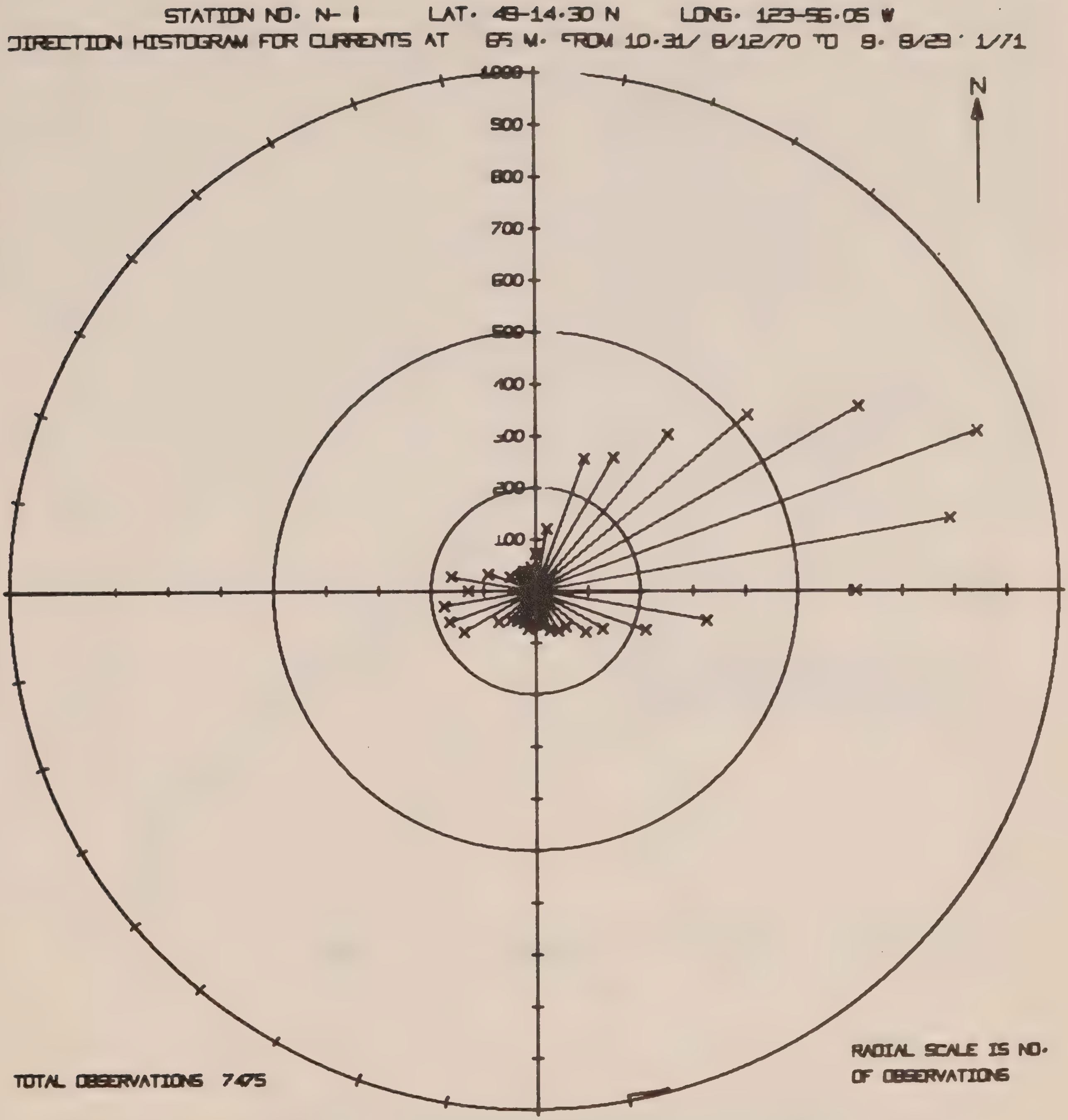


Figure 26b. Direction histogram for currents of Figure 26a.

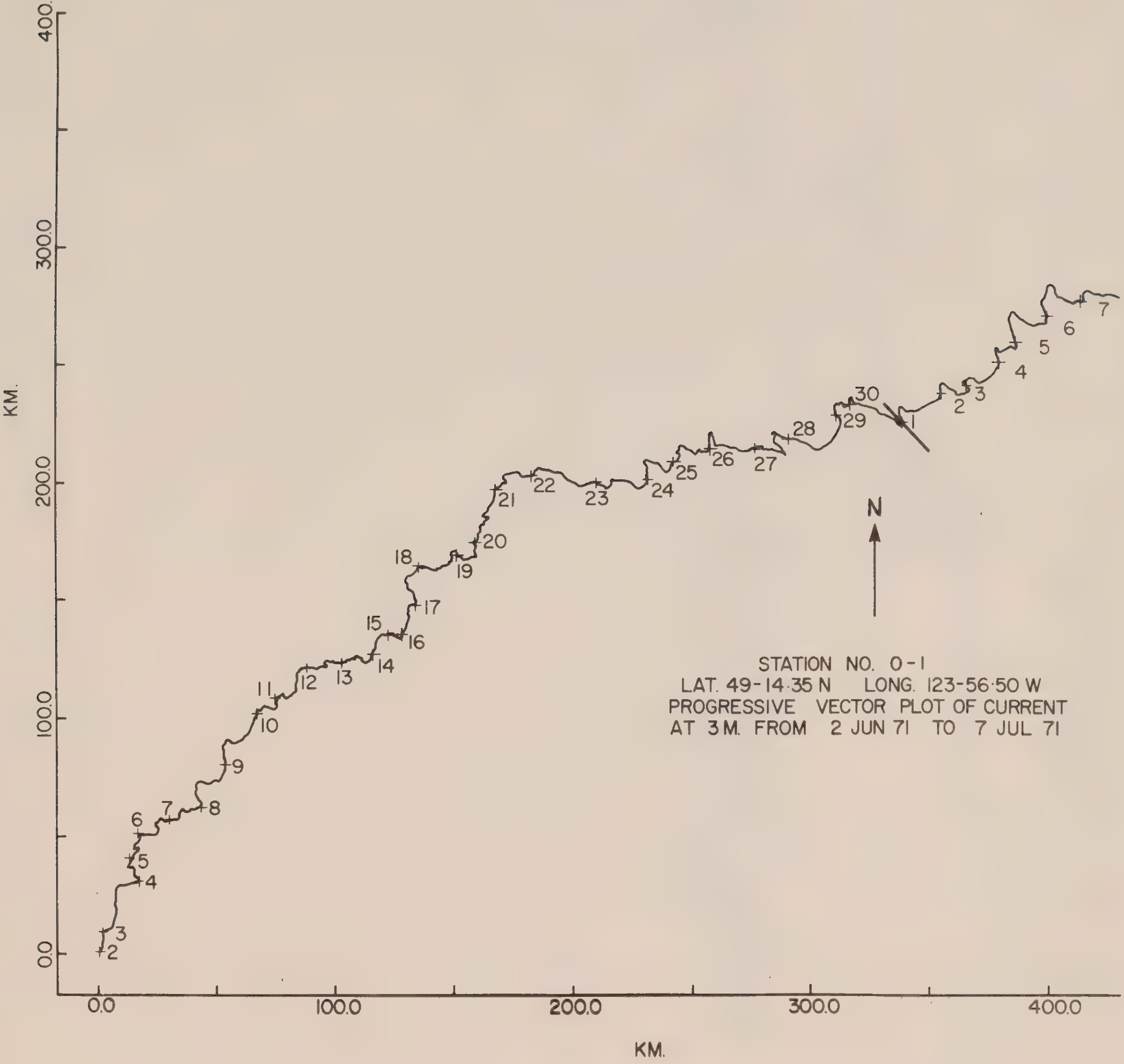


Figure 27. Progressive-vector diagram for currents at 3 m depth at N-01 (proposed outfall site). 2 June - 7 July 1971.

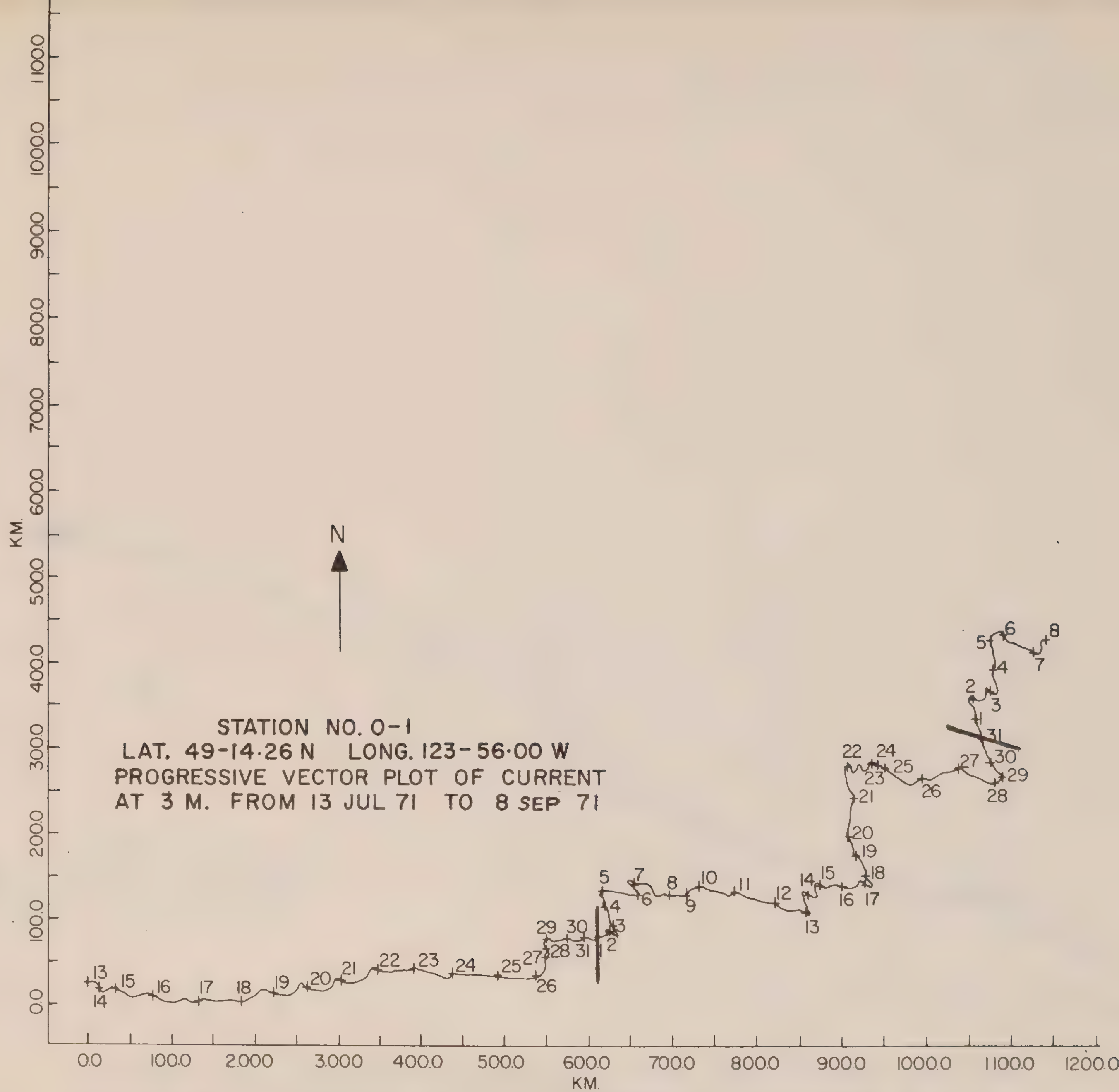


Figure 28. Progressive-vector diagram for currents at 3 m depth at N-01 (proposed outfall site). 13 July - 8 September 1971.

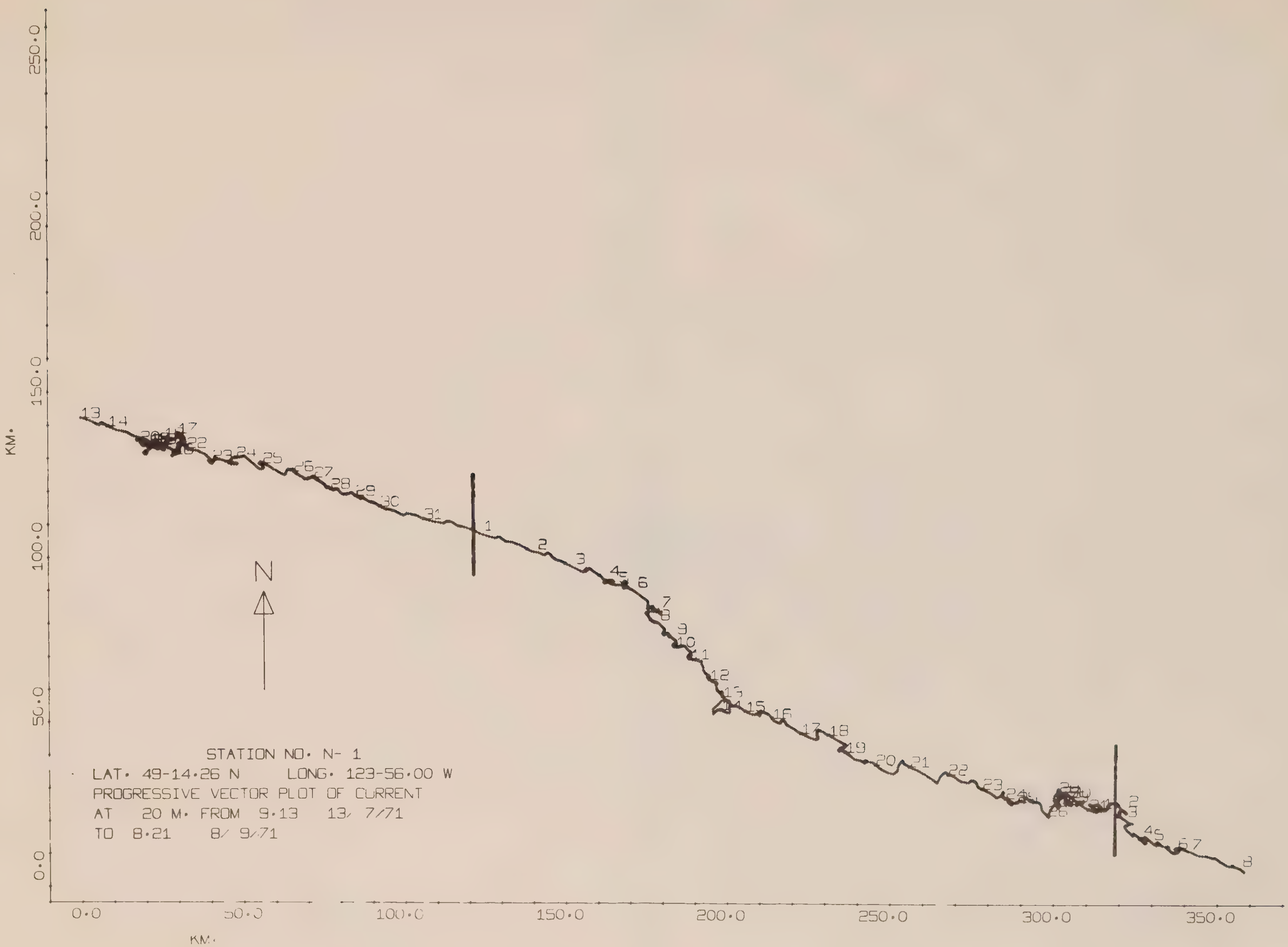


Figure 29a. Progressive-vector diagram for currents at 20 m depth at N-01 (proposed outfall site). 13 July - 8 September 1971.

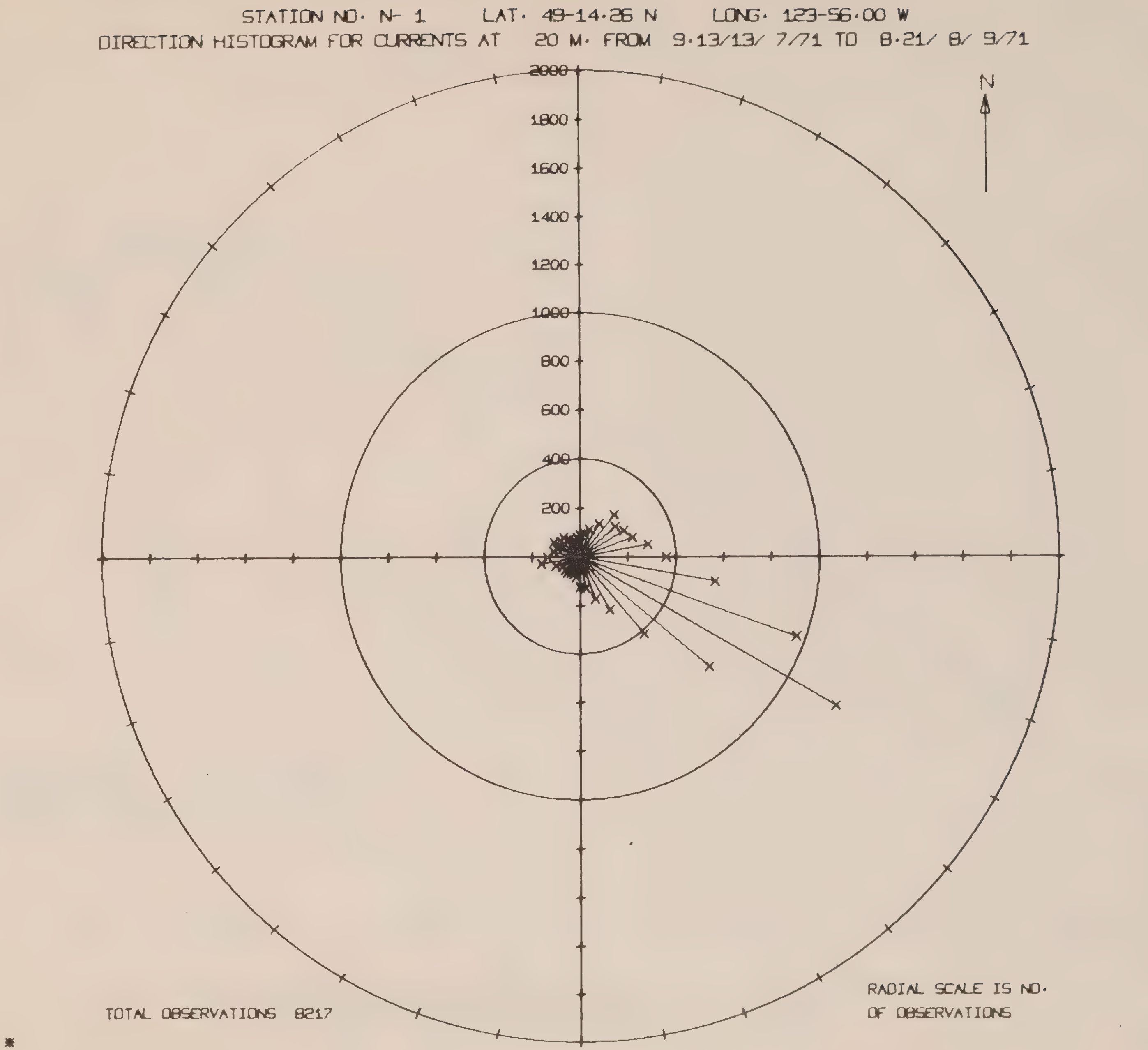


Figure 29b. Direction histogram for currents of Figure 29a.

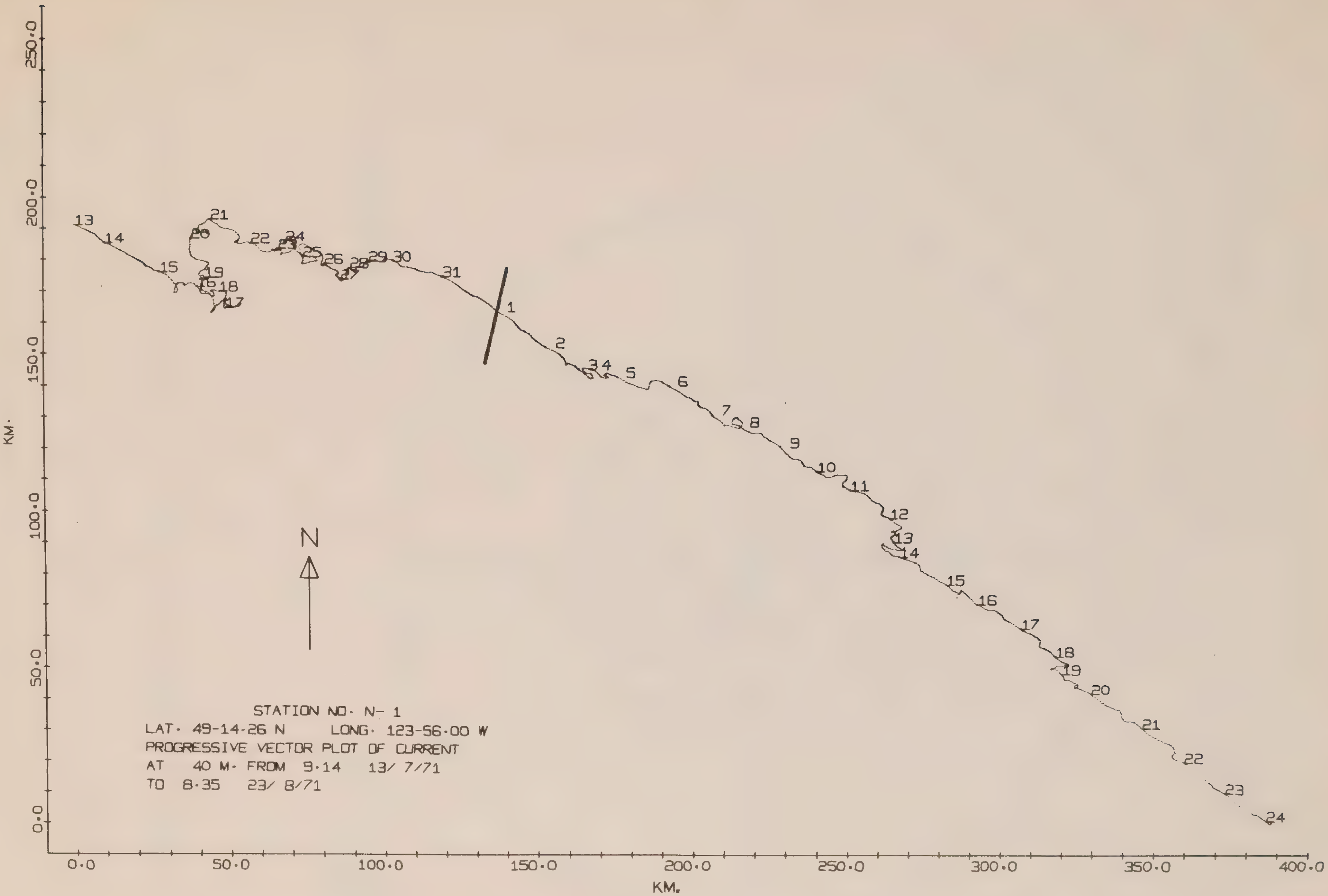
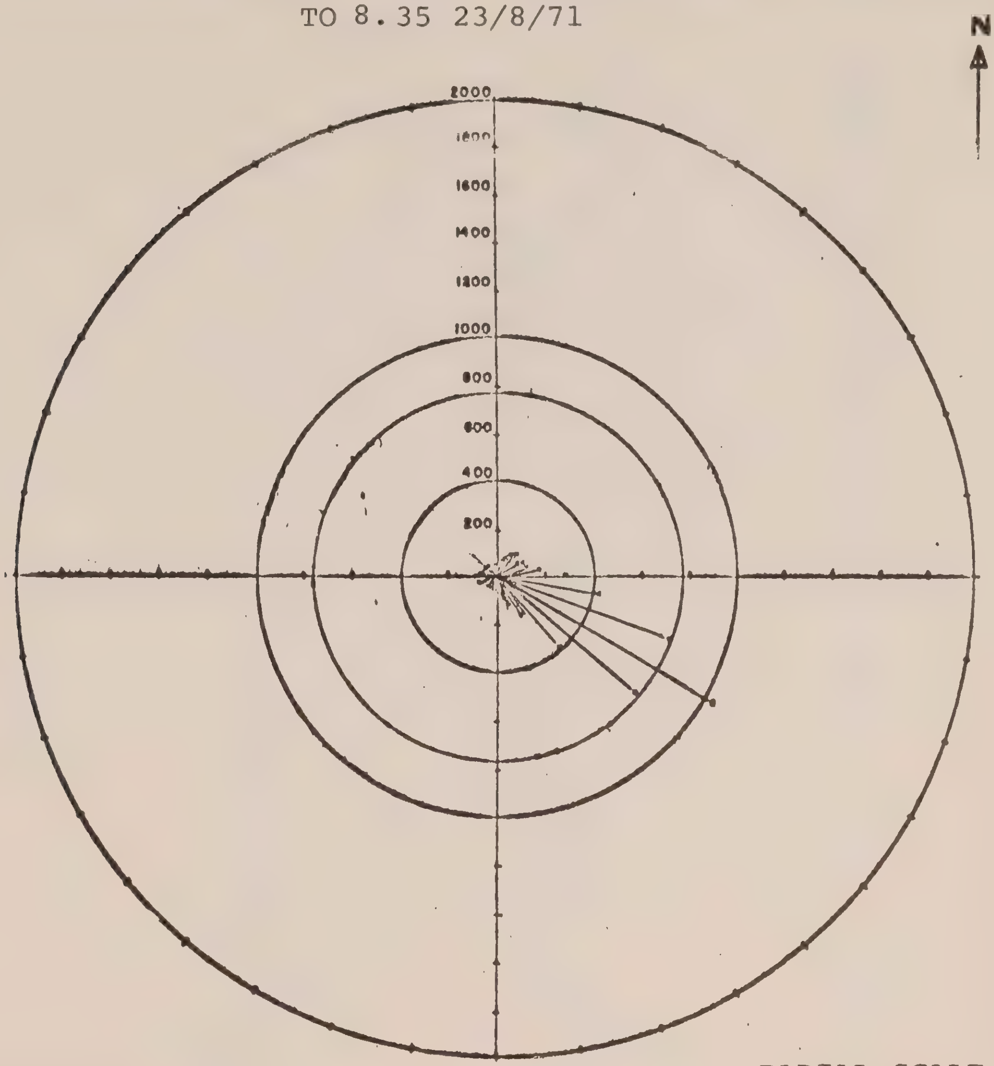


Figure 30a. Progressive-vector diagram for currents at 40 m depth at N-01 (proposed outfall site). 13 July - 24 August 1971.

STATION NO. N-1 LAT. 49-14'26 N LONG. 123-56'00 W

DIRECTION HISTOGRAM FOR CURRENTS AT 40 M. FROM 9.14 13/7/71

TO 8.35 23/8/71



TOTAL OBSERVATIONS 6081

RADIAL SCALE IS
No. OF OBSERVATIONS

Figure 30b. Direction histogram for currents of Figure 30a.

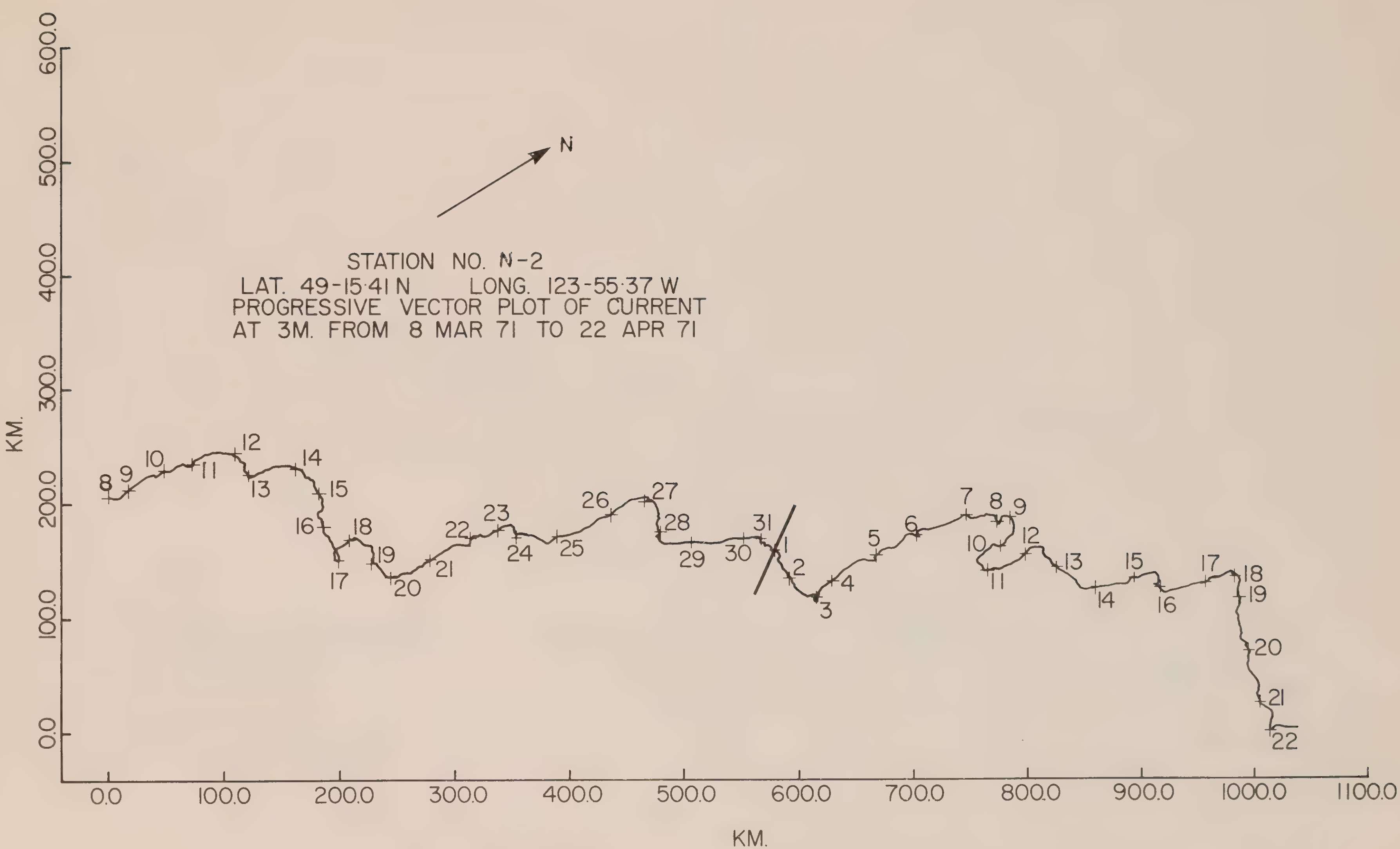


Figure 31. Progressive-vector diagram for currents at 3 m depth at N-02. 8 March - 22 April 1971.

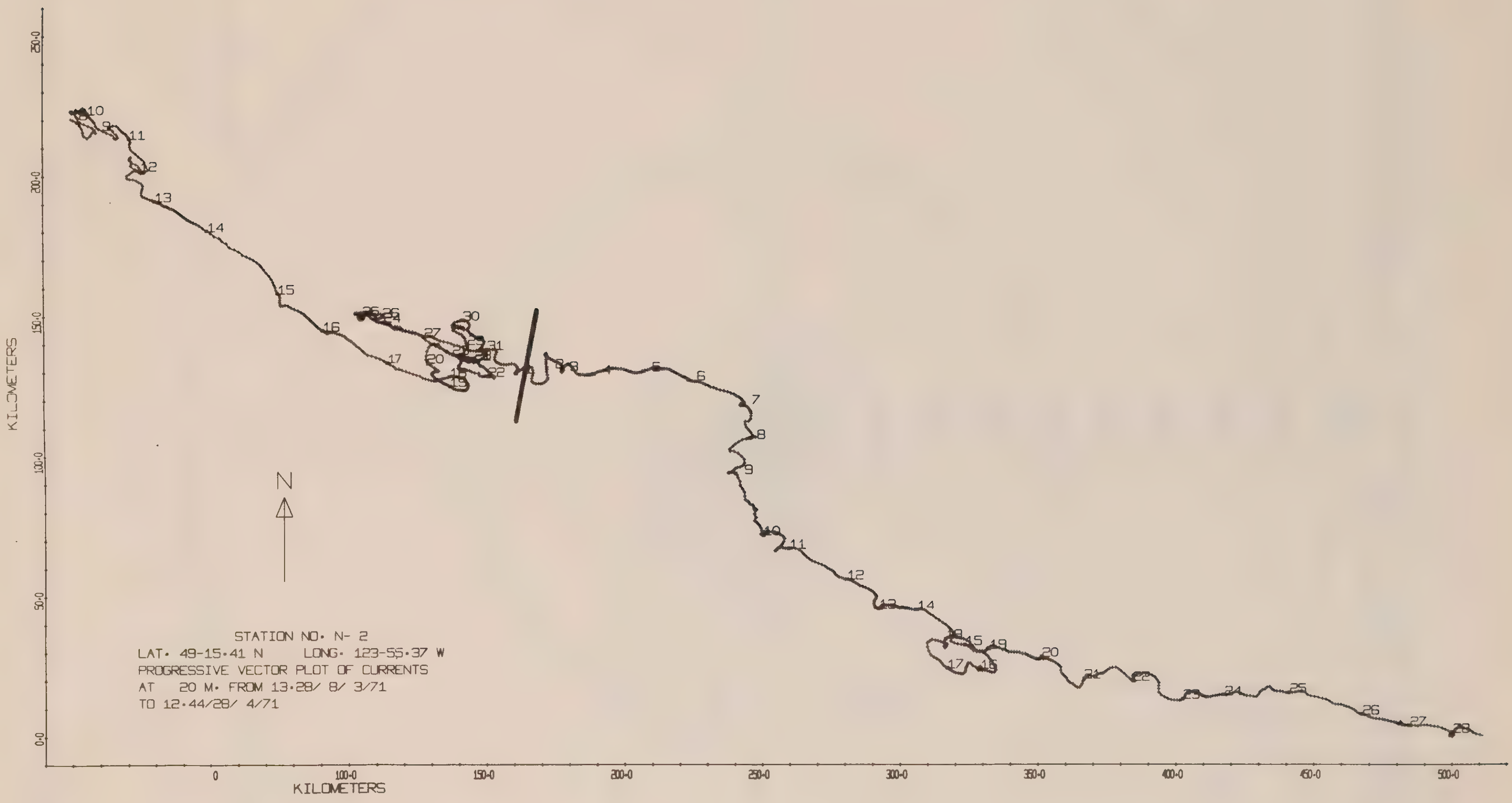


Figure 32a. Progressive-vector diagram for currents at 20 m depth at N-02. 8 March - 28 April 1971.

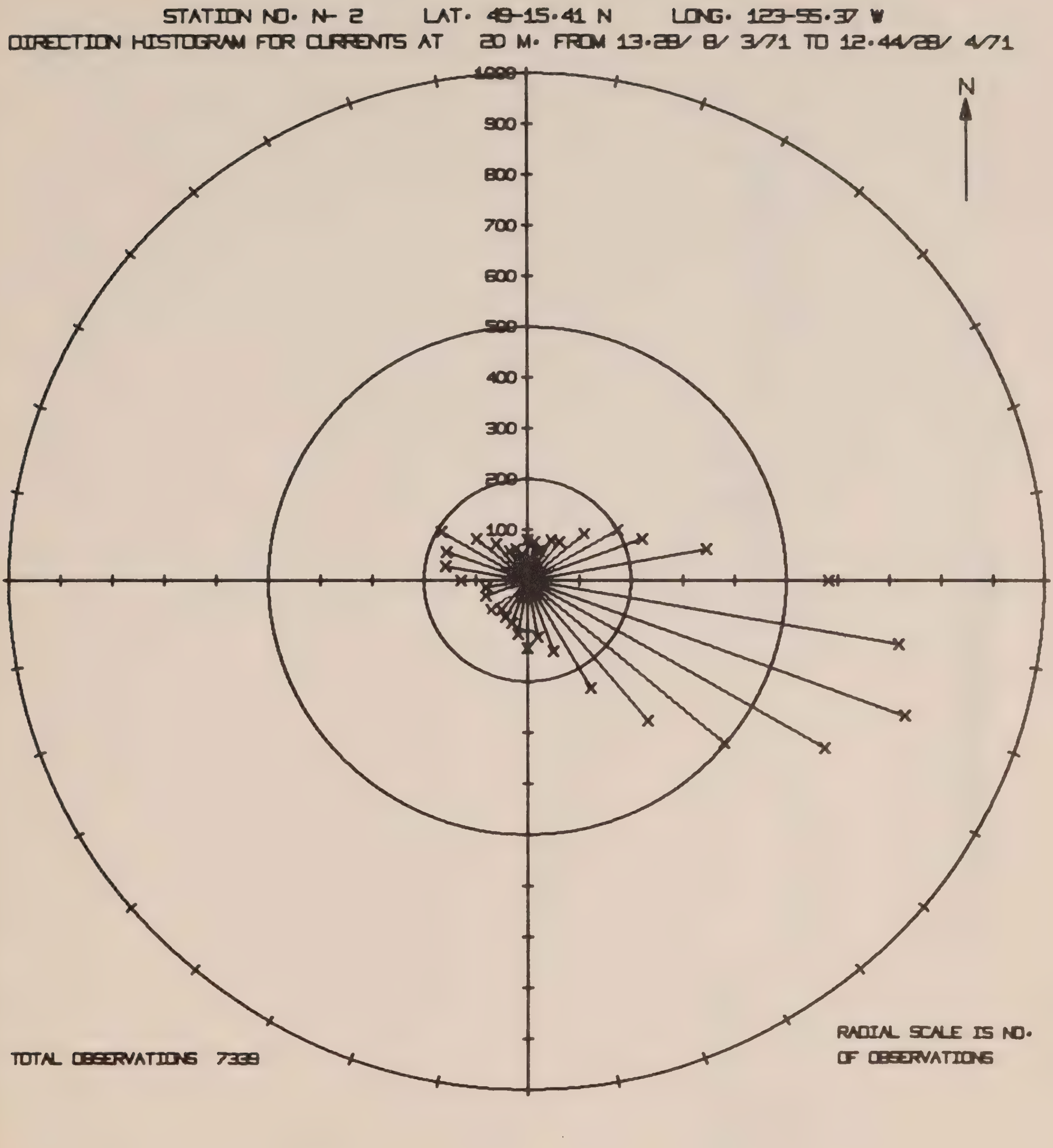


Figure 32b. Direction histogram for currents of Figure 32a.

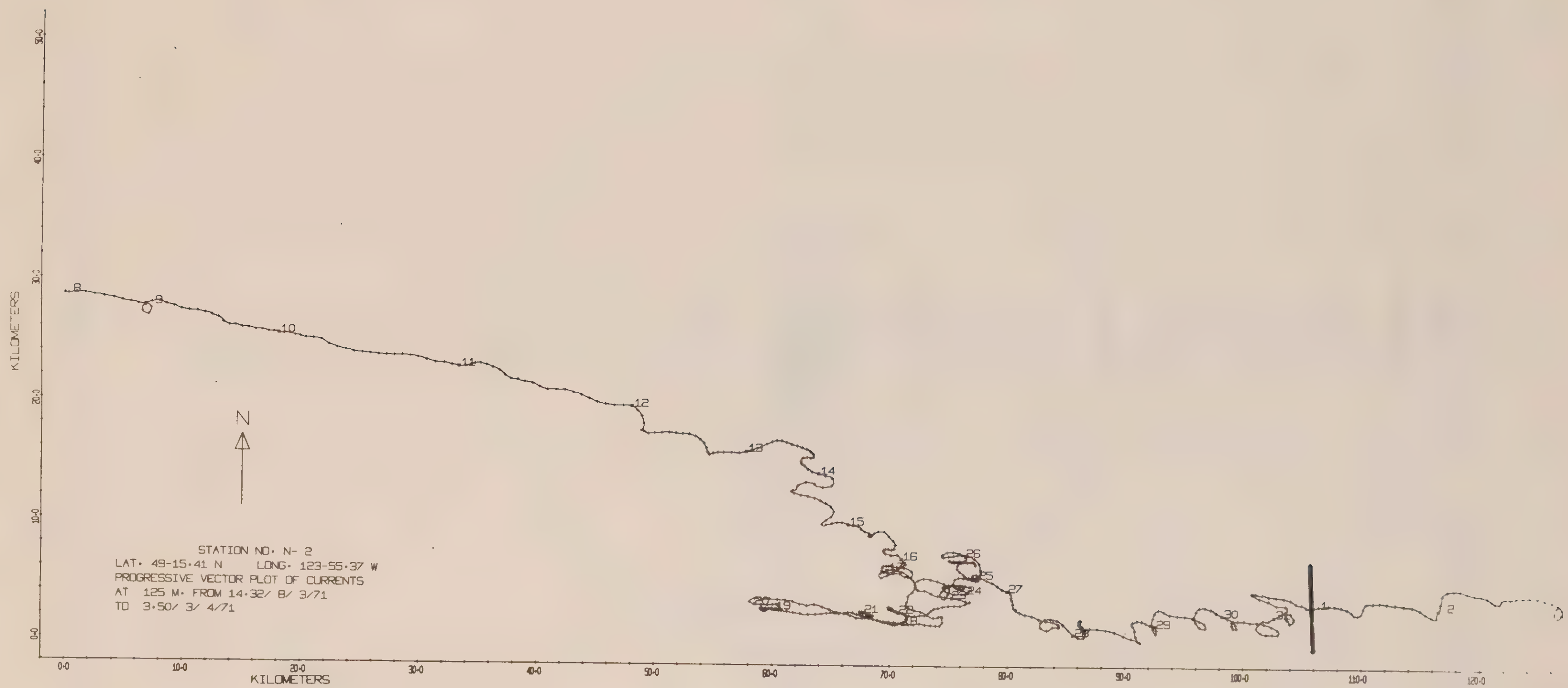


Figure 33a. Progressive-vector diagram for currents at 125 m depth at N-02. 8 March - 3 April 1971.

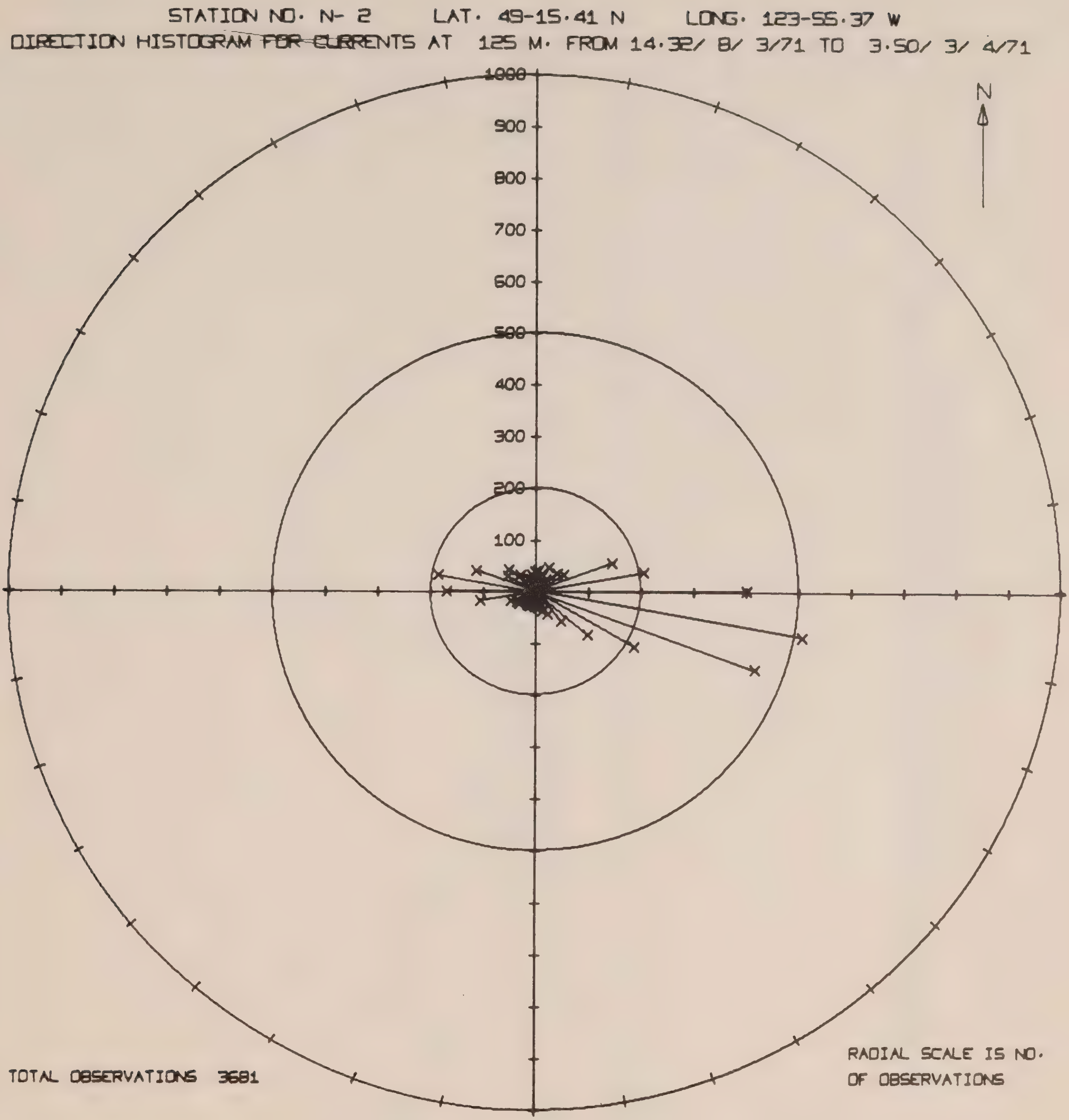


Figure 33b. Direction histogram for currents of Figure 33a.

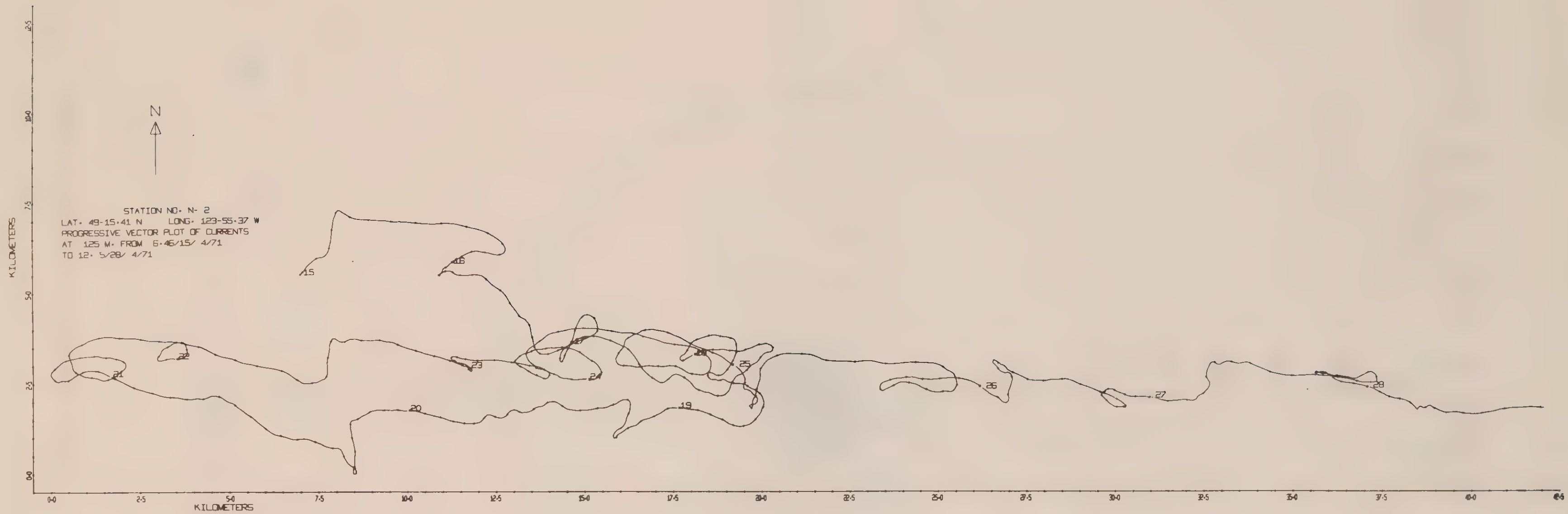


Figure 34a. Progressive-vector diagram for currents at 125 m depth at N-02. 15-28 April 1971.

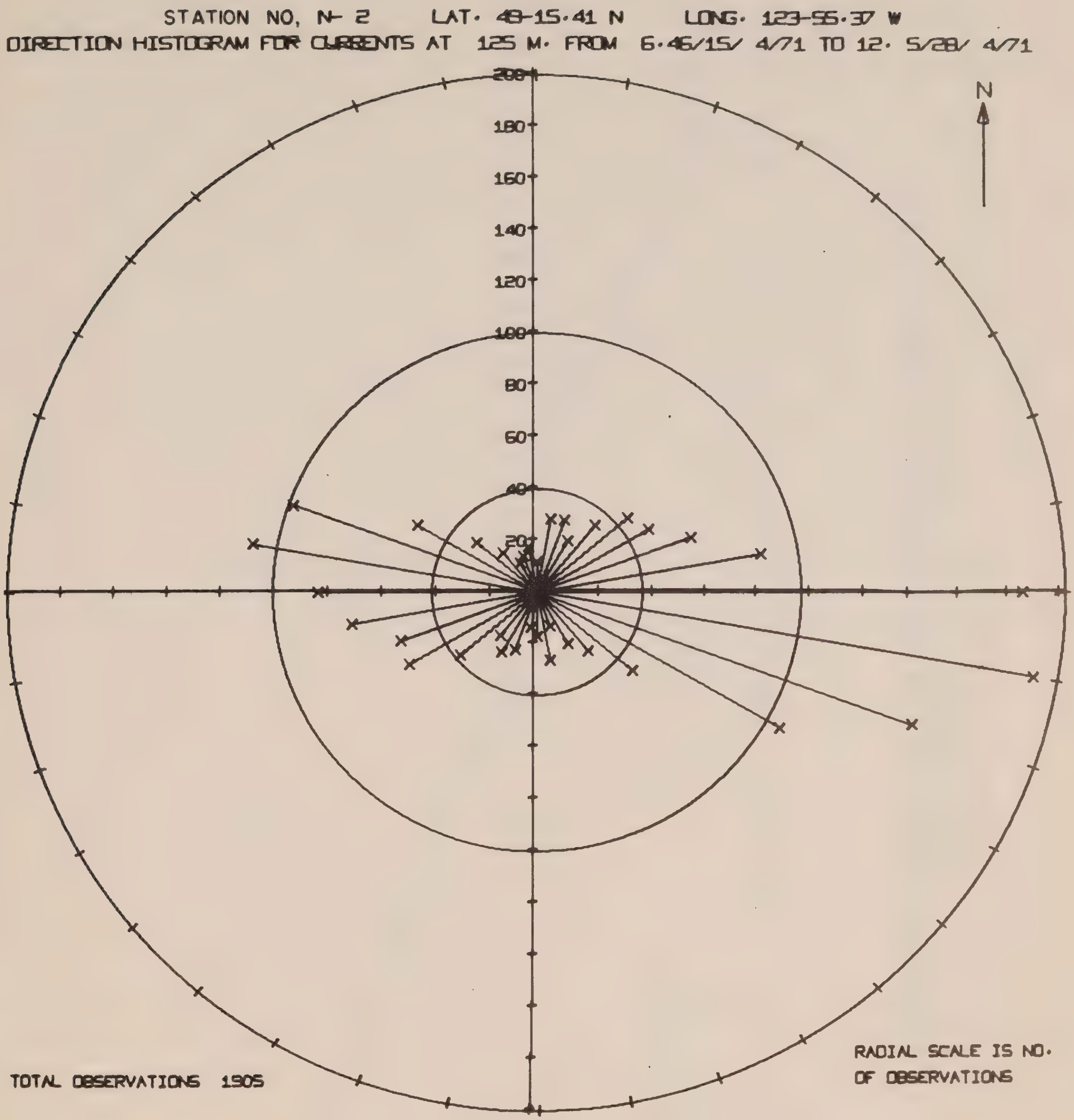


Figure 34b. Direction histogram for currents of Figure 34a.

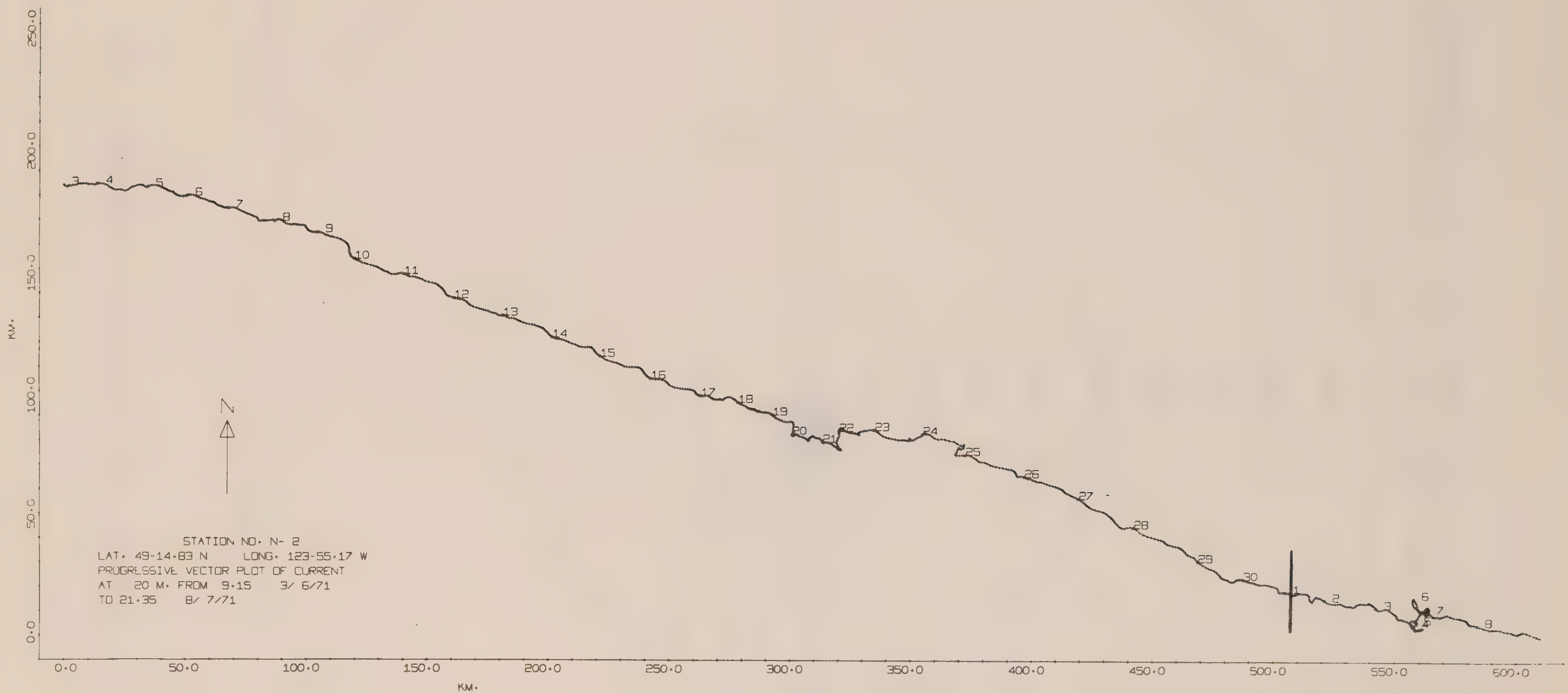


Figure 35a. Progressive-vector diagram for currents at 20 m depth at N-02. 3 June - 8 July, 1971.

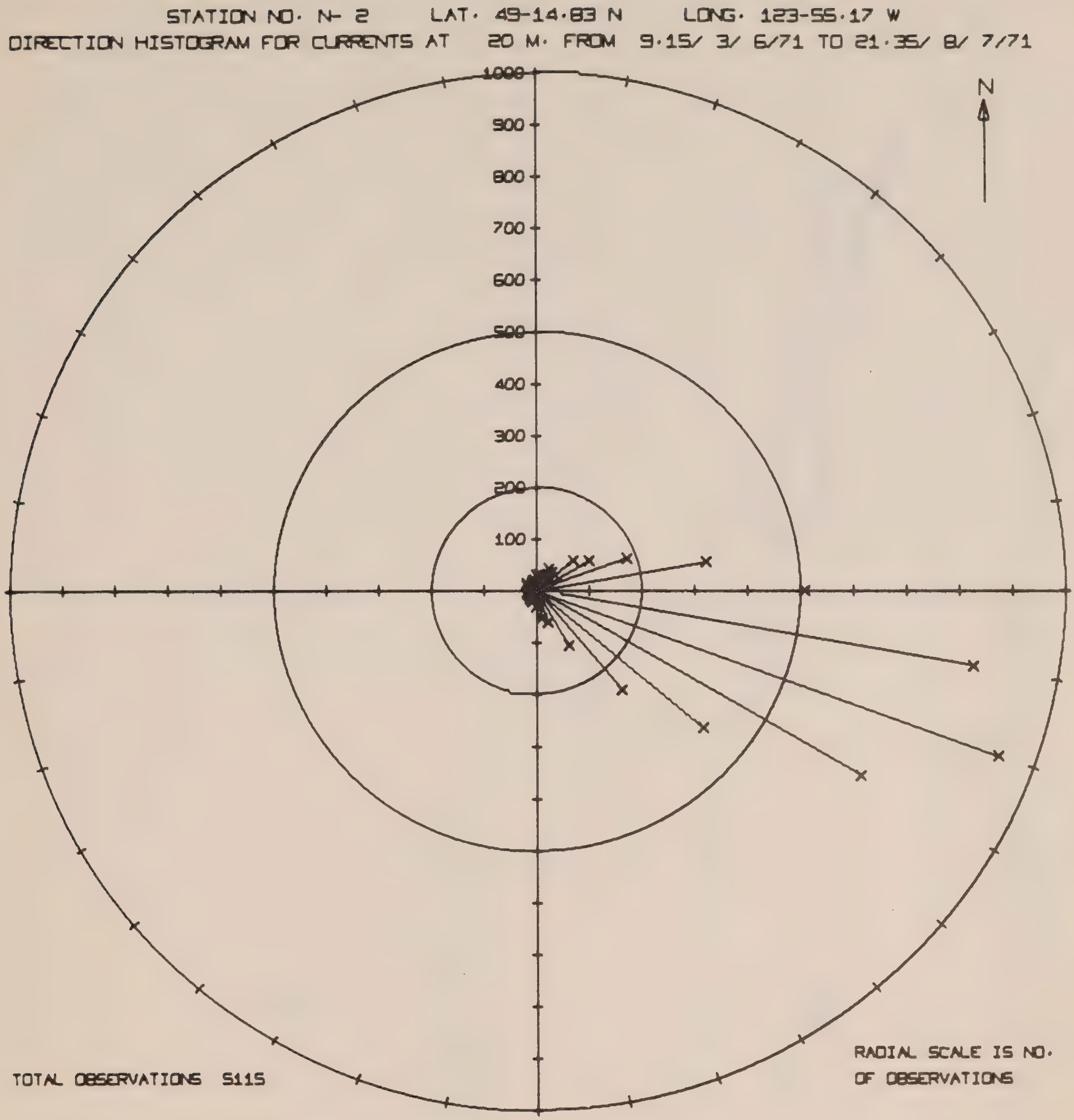


Figure 35b. Direction histogram for currents of Figure 34a.

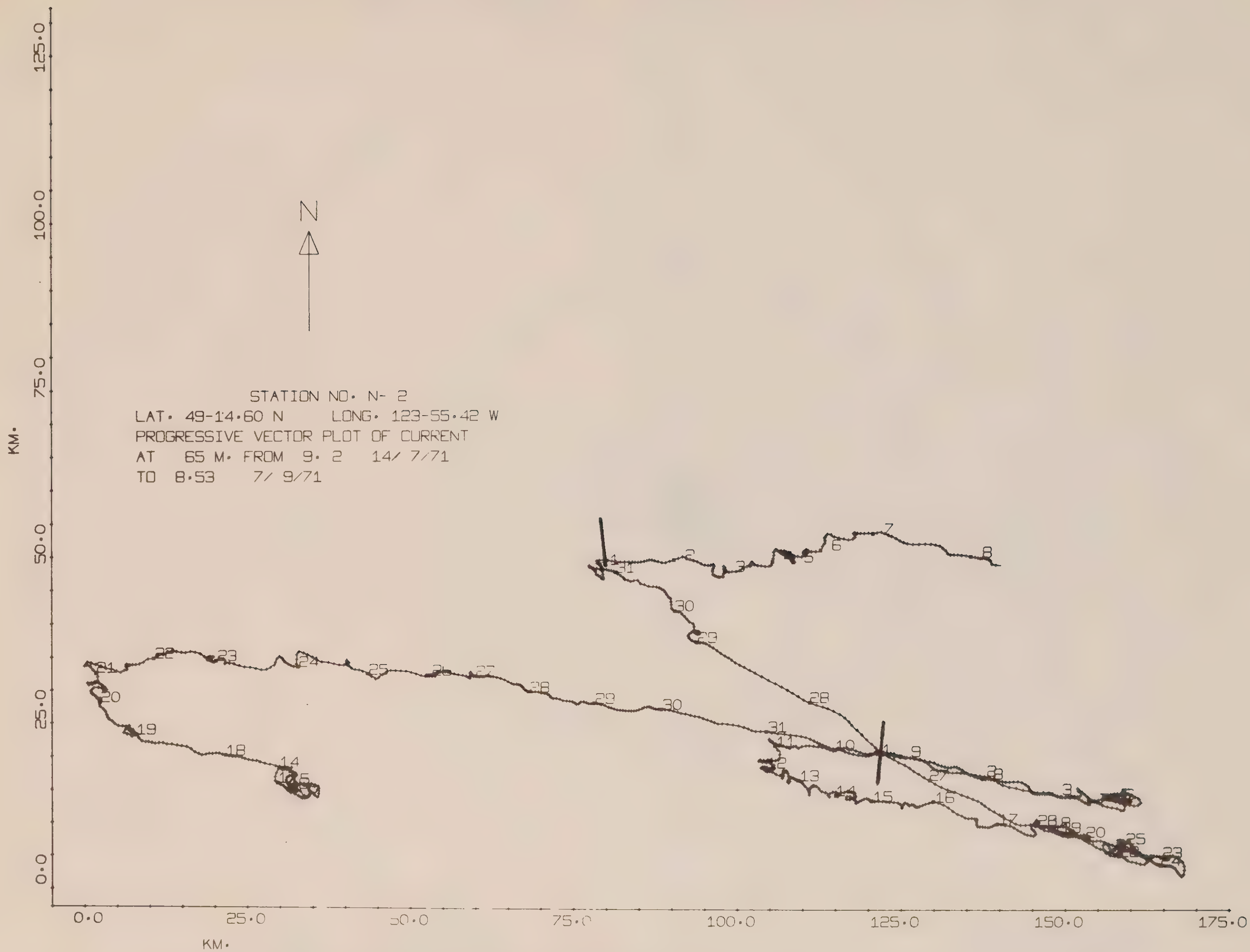


Figure 36a. Progressive-vector diagram for currents at 65 m depth at N-02. 14 July - 7 September 1971.

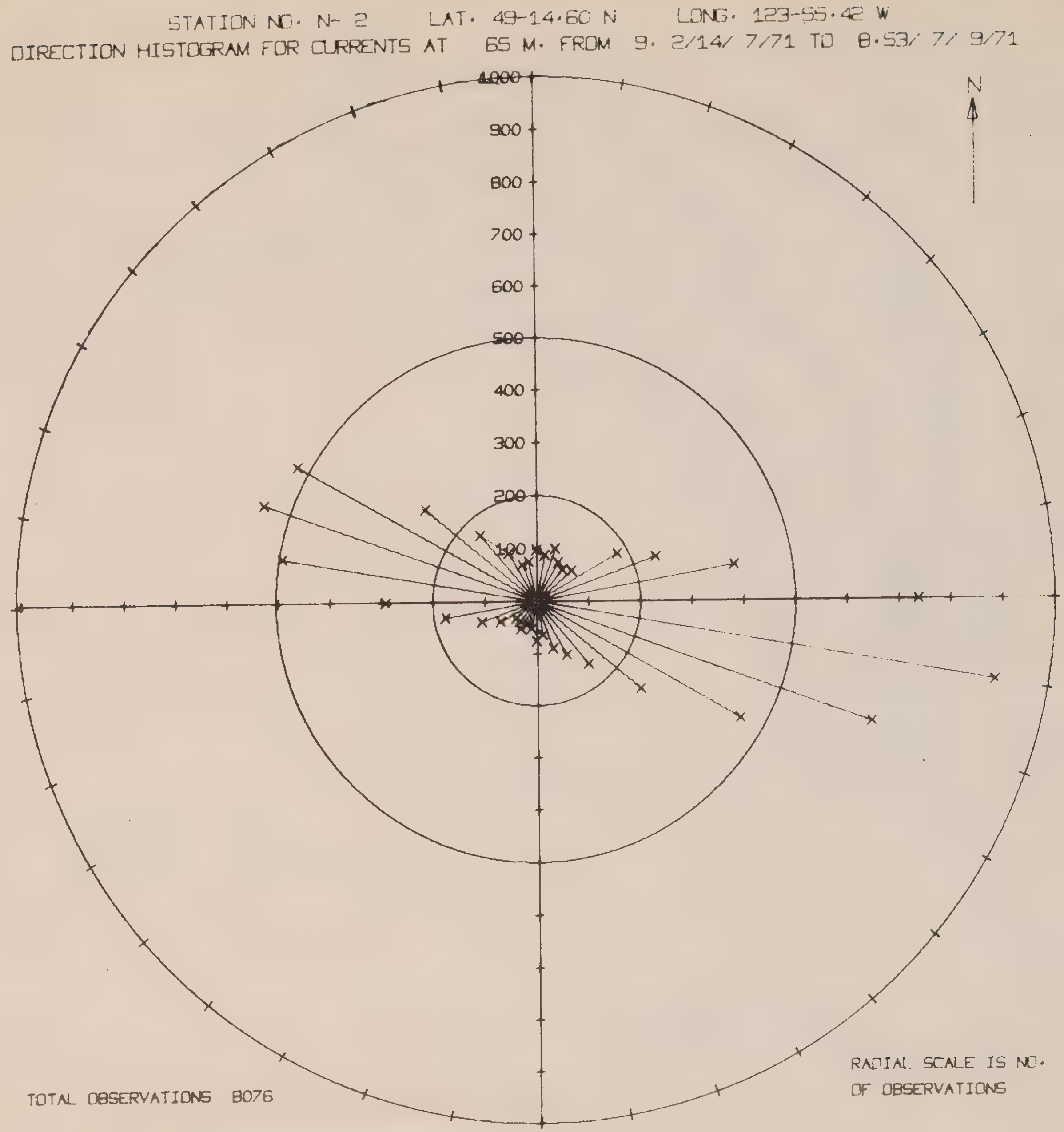


Figure 36b. Direction histogram for currents of Figure 36a.

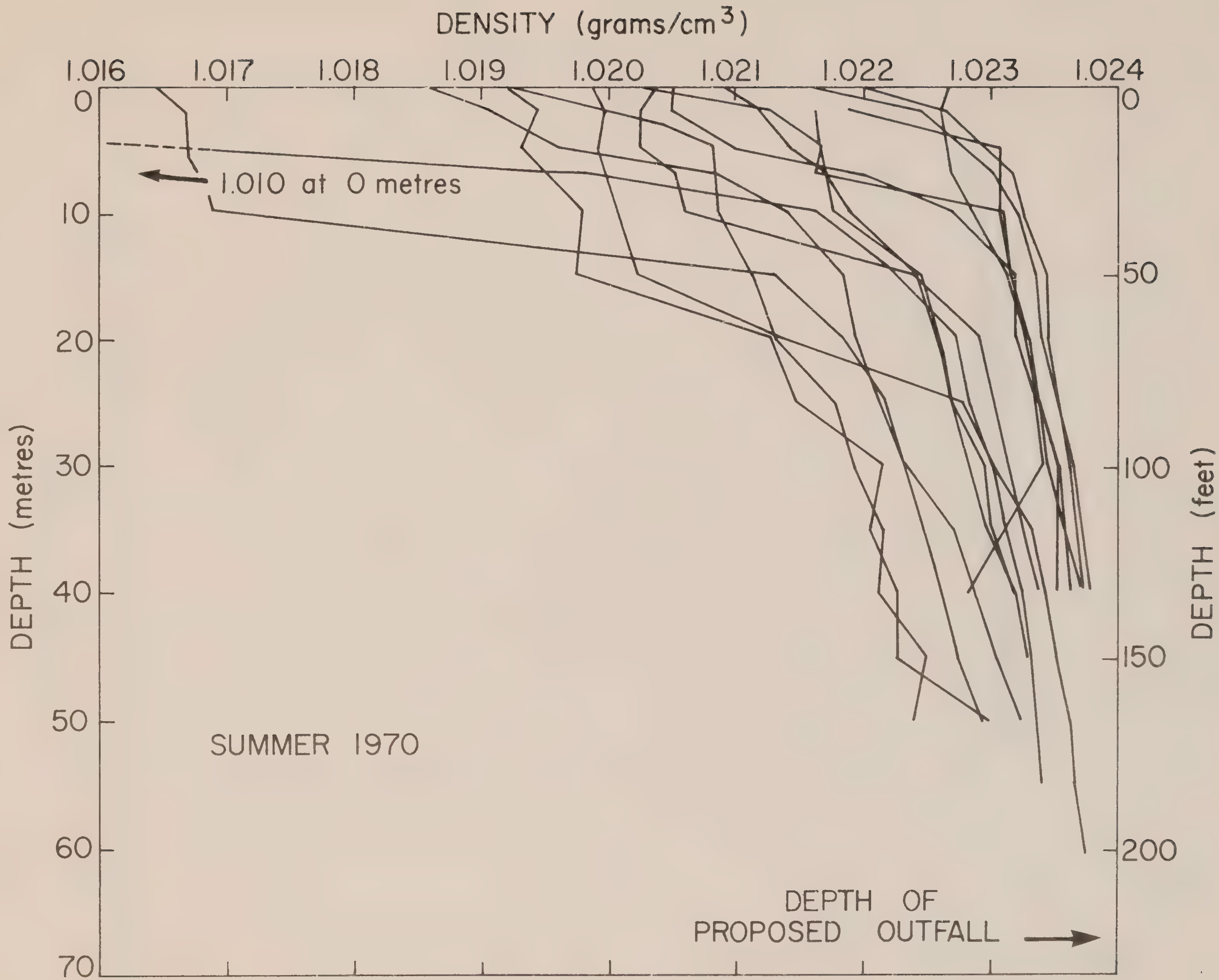


Figure 37. Density profiles at proposed outfall site. Summer, 1970.

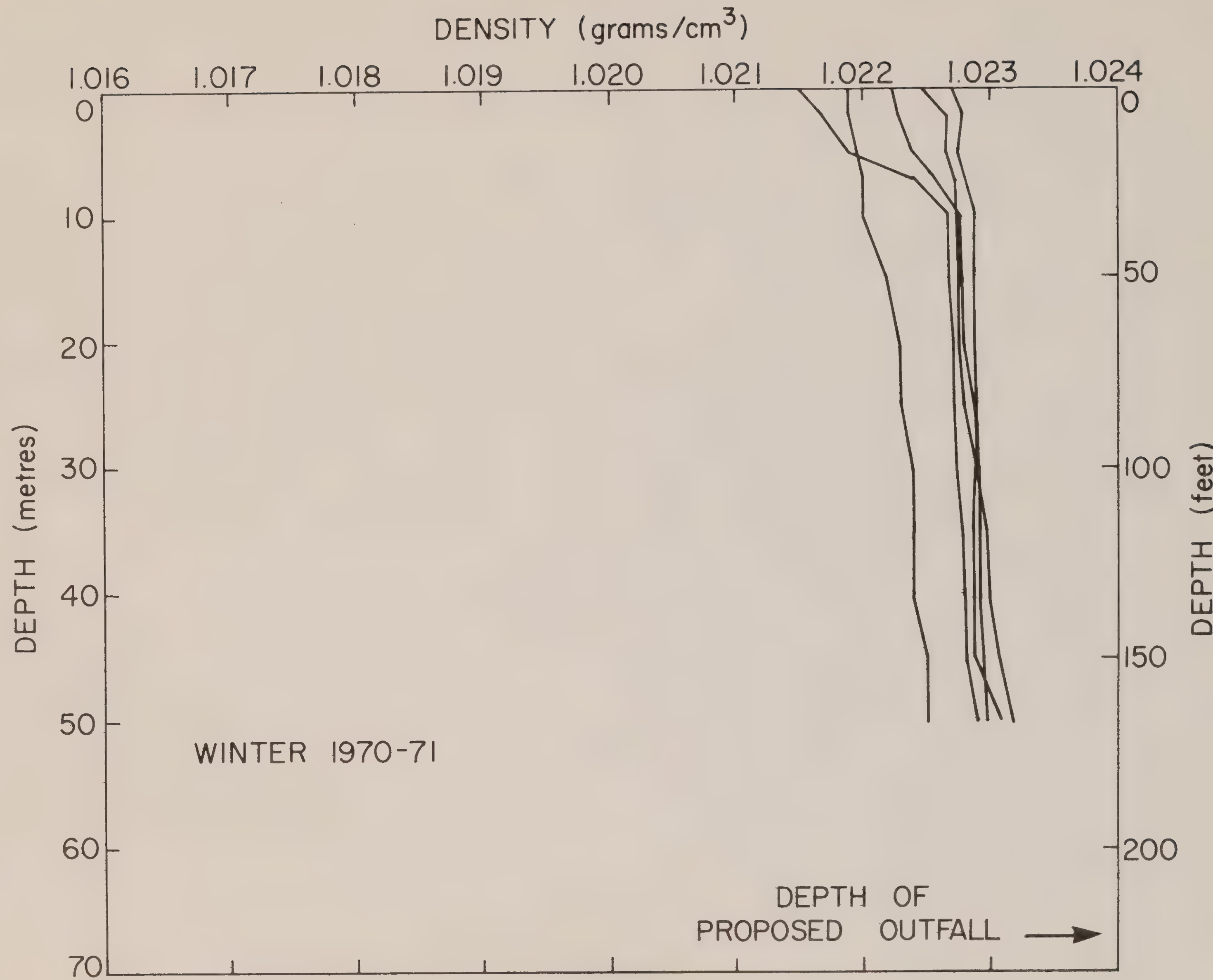


Figure 38. Density profiles at proposed outfall site. Winter, 1970-71.

Pacific Marine Science Report 73-13

THE EXCHANGE OF DEEP WATER IN HOWE SOUND BASIN

by

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NOVEMBER, 1973

ABSTRACT

An examination is made of the available historical oceanographic data for the main channel of Howe Sound over a 15-year period (1959-73). The basin water confined behind the sill in Howe Sound is subjected to occasional renewal by influxes of water over the sill. These influxes penetrate to various depths, depending on the relative density of the waters involved. Penetrations to mid-depths are of fairly frequent occurrence, while renewal at the deepest depths appears to occur at least every few years. The influxes across the sill seem to be related to strong down-channel winds and to heavy surface-water run-off, as indicated by comparisons between the time series for these quantities and the time series for water temperature, salinity, and dissolved oxygen content. Finally, an order-of-magnitude estimate of diffusion coefficients is obtained for the water confined in the basin.

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THE EXCHANGE OF DEEP WATER IN HOWE SOUND BASIN

INTRODUCTION

The inner portion of Howe Sound takes the form of a deep basin (Figs. 1, 2) bounded at the seaward end by a relatively shallow sill (Figs. 3, 4) with steeply-sloping sides. The circulation in the upper layers within (and without) the basin is typically estuarine in nature, i.e. it is influenced by fresh-water run-off, tides, and wind. However, the presence of the sill affects the circulation and properties of the deep water in the basin, so that these may be considerably different than for the water in the region just outside of the sill at comparable depths. The principal effect of the sill is to prevent the immediate and continuous passage of deep "outside" water, with characteristics representative of water from Georgia Strait, into the basin. Rather, the water resident behind the sill undergoes aperiodic (or perhaps quasi-periodic) renewals below sill depth, with exchanges extending completely to the bottom occurring every 3 or 4 years, apparently. The nature of this phenomenon is examined herein. It is suggested that, from time to time, relatively dense outside water presents itself at the sill where it pours into the basin as a density current seeking an appropriate equilibrium level. At other times, when the disturbance resulting from such a current has subsided, the deep basin circulation and water properties appear to be dominated primarily by diffusive processes.

An indication of the occurrence of deep-water renewals can be obtained by examining the dissolved oxygen (DO) content of the water at various depths. Generally speaking, the DO concentration tends to be gradually reduced at all depths below the sill level until an exchange occurs. Then its value is increased (apparently suddenly in most instances) to that of the replacement water, typically 3 to 4 ml/l. The depletion of DO presumably involves continuous oxidation of organic materials, together with some diffusion after the influx. The magnitude of the DO diffusion process must depend on the magnitude of the exchange, in addition to the concentration in the waters involved, since complete replacement would leave a nearly-homogeneous water mass in the basin, whereas limited replacement at some mid-depth might temporarily establish a prominent DO maximum.

Salinity is also a good indicator for the occurrence of exchanges. Since salinity is usually the major factor in establishing the density of water in Howe Sound, its value will be increased as a result of an exchange of water across the sill. In the periods between renewals, the salinity is gradually reduced by vertical diffusive processes. The temperature of the water involved in an exchange has much less influence on density than does salinity and, generally, does not provide as reliable an indicator of the occurrence of an exchange as do salinity and DO. The extent to which replacement has occurred over depth is indicated by the relative homogeneity of the water in all of its characteristics.

The renewals of deep basin water reflect exchanges of water with the region seaward of the sill (as suggested above) rather than with the surface layers within the basin. Evidence for this can be found in the frequent existence of a DO minimum at a depth of some tens of meters. Since there can be no transfer of oxygen through the minimum, any DO enhancement at such times must be due to exchange over the sill rather than to diffusion downwards from the surface. Further evidence is obtained from vertical sections of salinity or density *vs.* time for locations adjacent to either side of the sill, which indicate that water of the density involved in an exchange is available outside the sill at a level close to sill depth. Thus, the nature of the exchange (i.e. the extent and characteristics of the replacement flow) is due not so much to local influences within the basin as it is to the influence of water external to the basin. In particular, seasonal and non-periodic property variations in the deep water of the Strait of Georgia propagate into Howe Sound towards the sill location providing, at times, a source of water of relatively high density and DO content. The above notwithstanding, the actual "trigger" for an across-the-sill exchange does seem to be very often directly related to occurrences in the surface of the basin, rather than simply to a density difference across the sill.

Generally speaking, there should nearly always be some flow of replacement water at sill depth to compensate for the entrainment of intermediate water (by the fresh water

discharge at the surface) and its subsequent exodus from the basin as part of the "classical" estuarine circulation. Most of the time, however, the influx consists of water of about the same density as that of the basin water at sill depth. Water of higher density could appear outside the sill in the normal course of events because of the propagation from Georgia Strait (with an appropriate time lag) of the seasonal salinity maximum due to a minimum in the Fraser River run-off. On other occasions, the appearance of water of higher density at sill level might be induced by various mechanisms. For example, strong down-channel winds (Squamish winds) could result in some "set-up" of water seaward of the sill, requiring compensating adjustments in the density and pressure fields which would tend to tilt the isopycnols upwards in the vicinity of the sill. Although little historical wind data is available for Howe Sound, the Squamish winds are related to cold air masses overlying the interior of the province in the winter months (especially December through February). The presence of such cold air masses appears to correlate with some exchanges over the sill, as indicated in past data. These winter exchanges tend to penetrate deeply into the basin, possibly because the water outside the sill is likely to be most dense at this time of year. The viscous transfer of momentum could provide another mechanism for the induction of higher-density water at sill depth. Any large increase in surface outflow will likely result in considerably increased entrainment of intermediate water from the basin. Then, a greater replacement volume flow over the sill must also occur.

The momentum imparted to underlying layers of water by this relatively strong inward current might result in the "upwelling" of denser water to sill depth at the sill location. Such an increase in surface outflow could be caused by the June freshet in the Squamish River system or by abnormal autumnal rainfall. These particular events show some correlation with the exchanges, usually to mid-depths in the basin, indicated by past data. In all of the exchanges, the duration and intensity of the causal mechanism will influence the volume and characteristics of the replacement water. Of course, if water of sufficient density is lacking outside of the sill, no renewal of the deep basin water can take place. Then, the replacement flow is expected to maintain itself near sill depth within the basin.

The actual replacement volume can be found by measuring the depth through which the overlying resident water is raised. This is a relatively simple procedure if the exchange has penetrated to the bottom of the basin (and if the appropriate 'before' and 'after' data is available). For lesser penetration depths, Gade (1970) has worked out a system for determining the volume involved. Perhaps the simplest method of all, if semi-permanent maxima or minima in any property profiles (e.g. DO minimum) exist and are unaffected by the exchange, is to observe the change in depth of such features as a result of the influx. Note, though, that the influx itself may produce a temporary property extremum.

The actual depth of water over the sill is dependent

on the tides (in addition to the atmospheric pressure field and the wind). Thus, occasionally, when the density structure adjacent to the sill is just appropriate for exchange at low tide, periodic (diurnal or semi-diurnal) influxes may occur which would penetrate to some level not much below sill depth. The volumes involved would probably not be large in such instances. (This process might generate some of the microstructure occasionally observed in STD traces.) Also, there is normally only a gradual change in water properties in a horizontal direction along the axis of the Sound. Therefore, large periodic density changes near the sill are not likely to occur as a result of tidal advection.

As mentioned previously, if the density outside the sill is less than the density inside the sill at all depths greater than sill depth, no deep water renewal can occur by exchange across the sill. Then, the deep water will only be subject to exchange through the vertical diffusion process with overlying waters. This assumes that any extraneous advective processes of any appreciable magnitude (such as the "sloshing" around of a particular influx) have been damped out. In fact, horizontal exchange processes seem to be sufficiently strong in deep water to prevent the existence of any appreciable horizontal gradient for any great length of time. The primary effect of vertical diffusion is to lead the water mass towards homogeneity, i.e. to reduce the density of the deeper water and to increase the density (in the absence of any significant fresh water discharge) of the overlying waters. In this respect, the

eventual result could be similar to that of a major over-the-sill replacement of basin water, which also leads to homogeneity. However, the latter event usually occurs in a much more dramatic fashion than the former since exchanges over the sill are almost instantaneous when compared to the time scale of diffusion processes.

EXCHANGES INFERRED FROM HISTORICAL DATA (1959-1973)

An examination was made of the available data for Howe Sound over the period 1959-73. The Pacific Oceanographic Group (POG) conducted cruises in the area on (almost) an annual basis, making hydrographic casts at approximately 12 stations each time. The Institute of Oceanography at the University of British Columbia (IOUBC) did an occasional station in Howe Sound in the earlier years but, in 1972-73 made casts at a number of stations on a monthly basis. The Marine Sciences Branch (MSB) of the Department of the Environment did a series of monthly stations through 1968, and conducted two cruises in 1972.

The data were studied with a view to determining, if possible, when (and why) renewal was occurring of the deep water inside the sill. To avoid some confusion from clutter when looking over the long term, and to conform more closely to previous sampling rates, not all of the monthly data points were used for the years 1968 and 1972-73, but only those points obtained in December-January or June-July. A later, more detailed

examination was made over the periods for which the monthly data were available.

Figures 5, 6, and 7 show the long term time series for DO, salinity, and temperature, respectively, near Stn. 5. The actual station positions vary with different cruises. Data was used in each case from the closest available location to Stn. 5. The position of the station along the channel axis in the greater portion of the basin makes little difference to the data, as indicated by nearly horizontal isopleths, except near the time of occurrence of an across-the-sill exchange. Each property is plotted at 3 depths, namely 100, 150, and 200 meters. For the DO plot, it was noted that, wherever sufficient data points were available, the slopes of the lines joining these points were approximately equal. Therefore, lines with the same slope were extrapolated through individual points (where necessary) whenever succeeding DO values were higher than the preceding ones. The fact that the slopes were approximately equal is undoubtedly mere coincidence. The reduction of DO with time is due both to diffusion and oxidation, processes which should show some variation with position and time, so one would expect to observe considerable variation of the time series about a straight line if sufficient data were available (and, indeed, one does, as an examination of monthly data presented below will show). Hence, too much importance should not be attached to the straight lines (or their slopes) used in the present instance, except to note that some negative slope is expected in most circumstances. Any discontinuities in these

lines then suggest probable renewals of basin water, when the normal diffusion process is temporarily interrupted. The relatively arbitrary decision was made that, lacking any evidence to the contrary, the major discontinuities would most likely occur about January. This decision was based on the assumption that Squamish winds were triggering most of the exchanges. However, the June freshet, or other heavy run-off, could be responsible for some of the exchanges. For the salinity plot, the slopes of the lines between data points varied considerably and no attempt was made to obtain equal slopes on the lines projected through individual points. Discontinuities in the lines were indicated only where succeeding salinity values were higher than preceding ones. However, unusually small slopes between data points might also indicate possible renewals in the intervening period since, again, the diffusion process can normally be expected to establish some appreciable slope. For the temperature plot, the behaviour pattern is not so apparent as it is for DO and salinity, so all temperature data points were connected with straight lines without discontinuities. However, whenever a rather sudden change in deep-water temperature occurs, it is probably indicative of a major exchange of water across the sill.

An examination of Fig. 5 shows that renewal takes place more frequently at depths of 100 or 150 m than it does at 200 m. This is expected simply because of the more frequent availability, outside the sill, of water with a density appropriate to intermediate depths inside the sill, as compared to

water with a sufficiently high density to penetrate to the bottom of the basin.

An influx of water which does penetrate the deeper basin waters, but which is of insufficient volume to renew all of the basin, could actually result in a reduction of DO at intermediate depths. This is due to the uplifting of deep resident water with a low DO content by the new replacement water. Likewise, a reduction in DO could occur at a particular depth if the replacement water happened to have a low DO concentration. The phenomenon is observed in the 100 m trace of Fig. 5, where downward transitions of the sloping lines occur on three occasions. Each such occasion is accompanied by an indication of increases in DO or salinity at depths of 150 or 200 m. Therefore, the reductions in DO in these cases are probably due to the first cause suggested above, i.e. uplift. It must be admitted, however, that the sudden reductions in DO at 100 m could be converted into gradual reductions, in the figure, simply by permitting an increase in the diffusive rate at that depth. One must then explain why the DO concentration remains relatively unchanged at 100 m simultaneous with quite sudden changes in this quantity at greater depths.

When the water in the basin becomes almost homogeneous in DO or salinity, this is a good indication that a major renewal has occurred. Homogeneity can be noted by comparing values at various depths in the data listings from the hydrographic casts. It is shown more dramatically by plotting the

envelope of the data points over the depth of interest, as in Fig. 8. Here, the property values from the minimum and maximum depths in question have been plotted on a time base and joined with straight lines. The extent to which the lines approach one another gives an indication of the degree of homogeneity. Homogeneity may serve to point out exchanges which might otherwise go unnoticed by reason of the replacement water not differing greatly in its properties from the old resident water. An example occurs in the winter of 1967, where changes in DO and salinity, in Figs. 5 and 6, are slight (but definite), yet the envelope shows a relatively high degree of homogeneity. Figure 8 also indicates the range of values to be expected in the water properties over the depth range of 100-200 m.

It should be mentioned that homogeneity, as well as the occurrence of water renewal, can be determined from contoured plots of the vertical property distribution *vs.* time, instead of the previously-mentioned diagrams, but not as readily. That is to say, the vertical distributions are much more tedious to plot and still do not avoid the requirement for making some sort of extrapolation or interpolation over time. The interpolations are linear, if normal practice is followed, whereas it is reasonably certain that they should not be linear if an exchange has occurred in the intervening period. One advantage of the contoured distributions is the concise, but comprehensive picture they provide for the whole water column of interest. Examples are shown in Fig. 9 for DO, and Fig. 10 for salinity.

Figures 5, 6, and 7 were examined independently and estimates made from each about the occurrence of an exchange, and about its probable extent over depth. The results of this exercise are shown in Fig. 11. It can be seen immediately in this figure that the DO time series provided a basis for a few more estimates than did the salinity series (probably because of the use of the constant slope in the case of DO), and that the temperature series was not very productive of estimates (as previously indicated). In two instances, exchanges were suggested by the salinity traces and not by the DO, possibly because the concentrations of DO were about the same in the old resident water and in the renewal water. On two occasions (winter 1967-68, late 1971), the renewal as indicated by salinity changes precedes that indicated by DO changes. This is undoubtedly the result of poor guesswork in locating the discontinuities in the salinity or DO time series. The discrepancies can be easily rectified by redrawing the discontinuities.

Figure 11 shows some numbers in association with the various exchange estimates. These numbers, as indicated on the figure, refer to correlations between the estimates and some aspects of the fresh-water discharge from the Squamish River system in Howe Sound, and between the estimates and the air temperature anomaly at the Vancouver International Airport. The monthly-averaged time series for the discharge and the temperature anomaly are given in Fig. 12. The air temperature anomaly is used as a predictor for Squamish winds, since no wind data in Howe Sound is available prior to 1972. The rationale is that

unusually low monthly mean winter temperatures at Vancouver International Airport usually indicate a cold air mass lying over much of the province. The very cold air in the interior of the province tends to come rolling down the mountain valleys to the coastal inlets, gaining momentum all the way, producing strong down-channel winds with durations of a few hours to several days. These winds are very local and seldom show up well in the Vancouver International Airport wind record. It should be noted, however, that Squamish winds do occur on occasion when the air temperature anomaly is close to zero. Presumably, relatively short-lived cold air masses, which don't make too much impression on the monthly average, can generate the winds. Several instances of note are shown in Fig. 12. In early 1971, the wind was reported in the newspapers as gusting to 60 miles per hour in Howe Sound, whipping up 8-foot waves which caused some damage to marinas. In February, 1972, an anemometer located at the head of Howe Sound registered a maximum mean hourly speed of 50 mph, and was said to have recorded a maximum gust velocity of 94 mph. This particular wind had a duration of about 12 hours.

The estimates of Fig. 11 indicate that the deeper penetrations of renewal water tend to occur in winter. The correlations between Figs. 11 and 12 suggest that these winter-time exchanges are triggered most often by strong winds. Lesser penetrations often occur in late spring, apparently triggered by the Squamish River freshet. The seasonal difference in depth of penetration is probably explained by the seasonal difference in

density of the water outside the sill. The sparsity of data over much of the period under consideration makes this hypothesis difficult to confirm. However, the data which is available suggests that the density maximum at a given depth outside the sill tends to occur in the latter half of the year. For example, consider the occasions when the 30.5 ppt isopleth is shown by the data to be at or above the (arbitrary) depth of 125 m. There are 12 such occasions in 42 sets of data, taken during the years 1959-1973. Ten of these 12 occur in the months of September through January. Of the remaining 30 data sets, showing the 30.5 ppt isopleth to lie below 125 m, only 10 were obtained in this same period of year. A further difficulty lies in the rapidity with which the salinity can vary at a given depth, and in the relatively large range of variation possible. The data suggest that large excursions ($\sim$ 0.5 ppt of salinity at a 50 m depth) may occur on time scales not exceeding a month, and perhaps much less.

Vertical sections of salinity, plotted along the main channel axis of Howe Sound, are given for all of the available data sets in Figs. 31 through 72. The contour interval is 0.1 ppt. Contours are only shown below about the 30 m depth because of the steep gradients encountered above that depth. The relative homogeneity of the water in the basin is clearly indicated in the figures (by the isopleth spacing), as is the variation of salinity outside of the sill. The slope of the contours just inside the sill is indicative of the direction of flow of density currents (because of the close relationship between salinity and

density in Howe Sound). Thus, on occasion, it is possible to suggest the likelihood of an exchange on this basis. However, because of the considerable axial distances between stations, and because the isopleths are located by simple linear interpolation between data points, not much reliance can be placed on this type of evidence. Further, there is a basic difference between the estimates of over-the-sill exchange based on an examination of the axial sections and those based on an examination of the time series at a single point in space. In the latter case, there is little suggestion as to when an event may have occurred within the sampling interval so surmises must be "smeared" over this interval. Also, the flow associated with the event is, in effect, integrated over time to provide increased reliability of the estimate. In the former case, it may be possible to suggest a likelihood for the occurrence (or non-occurrence) of an exchange from an examination of the isopleth slopes, but it can only apply to a short time interval about the day on which the data were obtained. Additional reference will be made to some of these vertical sections in the following pages.

EXCHANGES IN 1968

Data is available for Howe Sound on approximately a monthly basis for the period December 1967 to January 1969. These data are primarily from a Marine Sciences Branch hydrographic cruise conducted by P.B. Crean and A.B. Ages, supplemented by one data set each from IOUBC and POG. The time series for DO, salinity, and temperature for the previous three depths

(100, 150, and 200 m), inside the sill at Stn. 32 (as designated by Crean and Ages), are given in Figs. 13, 14, and 15. Stn. 32 is about 5 km to the north of Stn. 5. No attempt was made here to establish discontinuities in the trends of the series, because of the time scale of the data. The points are joined by straight lines merely to aid the eye in examining the curves. However, it is generally true that the appearance of positive slopes in these lines (for DO and salinity) indicates a disruption of the normal diffusive processes in the basin.

Again, independent estimates were made from each figure about the occurrence and extent of over-the-sill exchanges. In December 1967, an influx of water appears to have started increasing the value of DO, salinity, and temperature at a depth of 100 m. This trend continued through to February 1968, with a substantial increase occurring in DO content at all three depths, although not in salinity except at 100 m. In May, an increase in DO at all depths is shown by the IOUBC data. This doesn't fit the trend at 150 or 200 m but does at 100 m, so the postulated exchange is probably real. There is also a sharp decrease in temperature at 100 m. In July, the 150 m DO value shows an increase. This suggestion of an exchange is not supported by any of the other curves, except that the 200 m DO value shows an increase the following month, perhaps indicating that a small amount of marginally-denser water came in over the sill. A similar situation occurs in October-November, where the DO concentration first shows an increase at 100 m, followed later by an increase at 150 and 200 m. The salinity and

temperature at 100 m increased throughout this period. However, there is an unexplained decrease in salinity at 150 m, coupled with an unchanging temperature (thus indicating a reduction in density and requiring the unlikely penetration by this water mass of the higher density water at 100 m). The probable reason is a mistake in the data, especially since the subsequent value in December again fits the trend implied by the other data. Beginning in December-January, an influx appears to have commenced, as shown by the DO series and the 200 m salinity value, although the salinity at 100 m continued to decrease for this period. That the exchange subsequently continued, probably culminating in February 1969, is suggested by the major increase in the DO content of the deep waters as shown by the data for the following May. In addition, although salinity values are decreased somewhat at this time, a marked reduction in temperature is also shown in the data. The resultant density of this water mass was sufficient to account for flow inward across the sill. These various estimates of exchanges are shown in Fig. 16. They are shown extended over the sampling interval because of the uncertainty of the beginning times of the phenomena in the interval between samples. It is possible that the exchanges may have continued only for the space of a few days.

Figure 17 shows the trace of sigma-t (σ_t) at sill depth (70 m) for two stations, one on each side of the sill. These curves were derived from contours of the vertical distribution of σ_t *vs.* time (Figs. 18 and 19). The shaded areas indicate the periods for which the density at sill depth at the station north

of the sill (Stn. 32) was less than at the same depth at the station just south of the sill (Stn. 33). Thus, the possibility of a density current flowing into the basin exists at these times. This doesn't exclude the same possibility at other times, because the density field could be changing on a time scale considerably less than the sampling interval. In the present case, there is some concurrence between each of the shaded areas of Fig. 17 and the suggested exchanges of Fig. 16. No shaded area corresponds to the influx postulated for October-November but the σ_t curves do approach one another quite closely during this period. A seemingly strange feature of the σ_t curves in Fig. 17 is that the water at Stn. 32 appears to become more dense after an influx than the water at Stn. 33 supposedly involved in the exchange. This is partly accounted for by the fact that Stn. 32 is actually well removed from the sill (about 10 km) and a density gradient exists between the station and the sill in the upper layers at the times in question. Stn. 33 (corresponding to Stn. 4 in Fig. 1) is immediately adjacent to the sill on its south slope. Thus, due allowance must be made for the effect of the gradient. This being done, the curves for the last half of the year would present no problem. The traces in August-September, for example, would indicate an influx of higher density water tending to increase the density of the water just north of the sill and leaving it with a somewhat higher density after the influx than it had before (but still with a density not greater than that of the incoming water at its maximum). In fact, the curves would probably show an additional shaded over-

lap area in October-November. However, this still leaves unexplained the situation occurring in April. Here, the density inside the sill appears to 'track' the density outside of the sill at a time when the latter is decreasing, but at the same time that an exchange is suggested. One would normally expect the trace for Stn. 32 to show a rising trend for the period of the influx. Thus, either some other mechanism is at work or the monthly sampling rate is too slow, strongly smoothing the curves because of aliased data.

Figure 17 also shows the air temperature anomaly, as before, and the weekly mean discharge from the Squamish River. There appears to be a correlation between the anomalously heavy discharge in January 1968 and an influx of water to a depth of at least 100 m, and possibly to 200 m or more. A suggested exchange in May appears to coincide with the onset of the river freshet. Exchanges are also postulated for June and July as the freshet progresses towards a peak, although the evidence is not so compelling as it was in the May data. Heavy run-off again occurred in October, with an influx over the sill as a possible result. Extremely cold weather prevailed in December 1968 and January 1969, concurrent with a possible renewal of basin water. As suggested above, however, the major portion of this exchange probably occurred at a slightly later date, after the temperatures had returned to its seasonal normal. Also, while no wind data is available from this area at the time in question, no reports of unusual winds have been encountered.

The vertical distributions of DO and salinity *vs*. time at Stn. 5 are presented in Figs. 20 and 21, respectively. The vertical sections of salinity, for the period under consideration, are given in Figs. 42 through 56. The slope of the isopleths in Fig. 42, for December 6, 1967, strongly suggests an influx of water into the basin at sill depth at that time. Other, less strongly implied influxes may be associated with the sections of May 23 (Fig. 47) and August 28 (Fig. 51). These dates again show some correspondence with the estimates of Fig. 16. Occasions when an influx is unlikely to take place are also indicated, for example, May 29 (Fig. 48) and January 22, 1969 (Fig. 56). Both of these dates are in conflict with Fig. 16. In the former case (Fig. 48), the evidence is weak. The latter case (Fig. 56) is most unusual, inasmuch as no other data in the period 1959-1973 show such an extreme sloping of the isopleths. No adequate explanation is offered for the large slopes. The conflict in the estimates may be due to the different time factors involved between the time series method and the vertical section method, as mentioned in the previous section.

The general conclusion to be drawn from the 1968 data is that this period was relatively uneventful. Most of the changes in oceanographic parameters were slight and the water exchanges were insipid. Nevertheless, the DO was abundantly replenished to depths of at least 100 m.

EXCHANGES IN 1971-73

Data is available in Howe Sound on approximately a monthly basis (with an occasional gap) for the period July 1971 to March 1973. These data were obtained primarily by IOUBC, with three data sets by MSB. The time series for DO, salinity, and temperature for the previous three depths (100, 150, and 200 m), at Stn. 5 inside the sill, are given in Figs. 22, 23, and 24. Again, the data points are joined by straight lines to aid the examination of the curves.

Estimates about the occurrence and extent of over-the-sill exchanges were made from each figure, as before. No DO measurements are available for the period August 1971 to February 1972, although values obtained at each end of this time period indicate that a renewal of basin water occurred on at least one occasion to a depth of 150 m or more. A relatively gradual increase in salinity, at a depth of 100 m, began in July 1971 and culminated about October of that year. This penetrated, in some measure, to 200 m, as indicated by a slight positive slope to the series. At the same time, there was some reduction in temperature over the whole water column below 100 m. There also appears to have been a slight influx of water, at 100 m, in November 1971. DO data is again sparce in the first half of 1972. There is a relatively large reduction in temperature in January-February at 100 m, followed subsequently by a reduction at 150 m. In June-July, both the salinity and DO data suggest an exchange extending to 200 m (except the increase in

salinity at 100 m is slight and appears to lag the changes in deeper water). All three time series suggest some changes in water structure in the basin in September-October. DO shows some increase at 100 and 150 m (although the change in this instance isn't much greater than the expected error in the readings). Salinity shows a slight increase at 200 m in this period, possibly extending to 150 m, followed by a sharp increase at 100 m during October-November. The temperature at 100 m increased much more rapidly than normal during September-November, confirming the other evidence for an influx of water. The relatively slight increase in DO in the first half of this period may just reflect the state of the incoming water, especially since this water was also quite warm. Likewise, in October-November, the DO values decrease, although the other series suggest an exchange. Presumably, the incoming water had a lower DO content than the resident water (which already had a relatively high content). From December 1972 to January 1973, a large increase occurred in the DO values at 150 and 200 m, bringing the water column below 100 m to homogeneity in this respect. Homogeneity of salinity and temperature is also indicated in January. Thus, it appears that the basin water has been almost completely renewed at this time. A further exchange in January-February seems likely, since the DO values at 100 and 150 m have again been enhanced, and there is a reduction in temperature. However, this is not confirmed by the salinity curve, which indicates decreasing salinity during this period, although a slight increase occurs at 150 m in the subsequent

time interval. These various estimates are shown in Fig. 25. Again, as with the 1968 estimates, they are shown extended over the whole sample interval, although the actual incursions may have taken place only over the space of a few days during the interval.

Fig. 26 shows the trace of σ_t at sill depth for stations on either side of the sill. These curves were derived from contours of the vertical distribution of σ_t *vs.* time (Figs. 27 and 28). The shaded areas indicate the periods for which the density at sill depth at the station north of the sill (Stn. 5) was less than that at the same depth at the station just south of the sill (Stn. 4). Thus, the possibility of density currents flowing into the basin is indicated for September and November in 1971, for a period beginning in February 1972, for an interval from October through December 1972, and for a time commencing in March 1973. Again, these curves don't exclude the possibility of density currents flowing for lesser periods than the sampling interval. There is some coincidence between each of the shaded areas in Fig. 26 and the suggested exchanges of Fig. 25. The area 'peaking' in November 1972 is of particular interest inasmuch as it shows the expected behaviour in general. Once the inflow begins, the density at the inner station follows the increase in density at the outer station, with some lag. Presumably, the lag is due to the fact that the density at the inner station is that of uplifted resident water. When the influx ceases, the inner station water density tends to remain relatively constant. A noteworthy feature of this particular

incident is the rapidity and magnitude of the increase in density of the water outside the sill.

Fig. 26 also shows the weekly mean discharge from the Squamish River and the weekly total wind mileage in the sector from NW to E, inclusive. Wind records became available early in 1971. The winds are measured at the head of Howe Sound (FMC Chemicals plant), approximately 17 km distant from the sill. However, it is generally true that down channel winds at the sill coincide with NW-E winds at the inlet head, especially if their duration exceeds an hour or two, because the mountainous sides of the inlet keep the flow confined. Influxes suggested in Fig. 25 as perhaps extending to 200 m coincide with the river freshet in both 1971 and 1972. There are no large anomalous discharges over the period considered except, perhaps, in March 1972. At this time, there is also a suggestion of some replenishment of DO at 100 m. Strong winds occurred in December 1971, coinciding with a large negative anomaly in air temperature. Strong winds likewise prevailed in the latter part of January 1972. For both of these occasions, DO data is lacking. However, DO samples which bracket the period in question do show that renewal has occurred at some time to a depth of 150 m or more. Also, the salinity time series suggests that an exchange may have occurred in December and the temperature time series indicates a similar possibility for January. It is noteworthy that high wind speeds, including gusts up to 94 mph, occurred for a period of 12 hours during the course of an MSB cruise in February 1972, but did not result in any substantial value for the

weekly total mileage. It is possible, though, that the DO replenishment mentioned above may have been caused by this particular gale rather than by the anomalous discharge. Periods of strong winds occurring on various occasions from October 1972 through February 1973 may be largely responsible for the series of exchanges postulated, in Fig. 25, for this same time span. There are five such periods shown in the wind data and, approximately, the same number of exchanges suggested by both the DO and salinity time series.

The vertical distributions of DO and salinity *vs.* time at Stn. 5 are presented in Figs. 29 and 30, respectively. The vertical sections of salinity, for the period under consideration, are given in Figs. 58 through 72. The section for October 14, 1971 (Fig. 60) suggests that an exchange may be taking place at that time. There is a good slope on the isopleths near the sill and nearly homogeneous water in the bottom half of the basin. There is also water of comparable characteristics outside the sill. Unfortunately, no data were taken just south of the sill on this occasion. In subsequent sections through to February 1972, near-homogeneity is still maintained but all of the values are progressively lower because of diffusion. An exchange over the sill appears to have been 'caught in the act' in November 1972 (Fig. 60). The influx is in the process of mixing in with the resident water. High-density water is apparent near sill depth, on the outside of the sill. This exchange appears to continue into December, at least. Subsequent sections show that the basin water becomes, again,

almost homogeneous. The remarks of a previous section, concerning the differences in estimates obtained from axial sections as compared to those obtained from time series, apply here as well.

Generally speaking, the latter part of 1971 and the first part of 1972 were relatively 'quiet' periods inside the basin in Howe Sound. A significant influx of water commenced in mid-1972. It proceeded either in steps or, if continuous, then rather more slowly than might have been expected. It culminated in homogeneity of the basin water mass, in all of its properties, in January 1973.

DIFFUSION COEFFICIENTS

A brief examination of the diffusion process was made to determine typical values for the vertical diffusion coefficient in Howe Sound, especially for those periods when data was available on a monthly basis.

Diffusion coefficients were calculated from a simple adaptation of Proudman's method for the stationary case (Proudman, 1953), which utilizes a vertical section over space at a given time for the property in question, to the non-stationary case, using a vertical section over time at a given point in space. Starting with the diffusion equation in the form:

$$\frac{\partial S}{\partial t} + \frac{u\partial S}{\partial x} + \frac{v\partial S}{\partial y} + \frac{w\partial S}{\partial z} = \frac{\partial}{\partial x}\left(K_x\frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial S}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial S}{\partial z}\right)$$

it is assumed that $\frac{\partial S}{\partial x}$, $\frac{\partial S}{\partial y}$, and w are negligibly small. This would appear to be the case during periods of relative quiescence

in Howe Sound basin. It is also assumed that K_z is independent of z over the depth range involved in any given determination. Then the equation above may be written:

$$K_z = \frac{\partial S}{\partial t} \Big/ \frac{\partial^2 S}{\partial z^2}.$$

Referring to Figure 73, three salinity isopleths (S, S_1, S_2) are given. Each curve is separated from its neighbour by a salinity increment, ΔS. A point, P, is chosen on S and the tangent to S at P is constructed. The slope of this tangent is $\Delta z/\Delta t$. A horizontal line through P is projected to intersect S_1 and S_2 at points A and B, respectively. The distance AB is equal to Δt. Vertical lines are drawn through A and B to intersect the tangent at points C and D. The distance CD is equal to Δz, the numerator in the slope expression. Another vertical line is drawn through P to intersect curve S_1 at point E and curve S_2 at point F. The distances EP and PF are designated δz_- and δz_+, respectively. If $\delta z_- = \delta z_+$, the method fails, because $\frac{\partial S}{\partial z} = 0$. At point P, the salinity is not changing along the tangent, so:

$$dS = \frac{\partial S}{\partial t} \cdot dt + \frac{\partial S}{\partial z} \cdot dz = 0$$

or:

$$\frac{\partial S}{\partial t} = - \frac{\partial S}{\partial z} \cdot \frac{\Delta z}{\Delta t}.$$

Approaching P from above (i.e. travelling from curve S_1 towards curve S):

$$\frac{-\Delta S}{2} = \frac{-\partial S}{\partial z} \delta z_- + \frac{1}{2} \frac{\partial^2 S}{\partial z^2} \delta z_-^2 - \ldots\ldots$$

Approaching P from below:

$$\frac{\Delta S}{2} = \frac{\partial S}{\partial z} \delta z_+ + \frac{1}{2} \frac{\partial^2 S}{\partial z^2} \delta z_+^2 + \ldots\ldots$$

Adding the latter two equations:

$$0 = \frac{\partial S}{\partial z} (\delta z_+ - \delta z_-) + \frac{1}{2} \frac{\partial^2 S}{\partial z^2} (\delta z_+^2 + \delta z_-^2) + \ldots\ldots$$

Substituting these results into the diffusion equation:

$$Kz = \frac{1}{2} \cdot \frac{\Delta z}{\Delta t} \left(\frac{\delta z_+^2 + \delta z_-^2}{\delta z_+ - \delta z_-} \right).$$

This can be applied to suitable regions of the property contours on depth-time plots, such as Figures 20, 21, and 30 for DO and salinity. Some values obtained from these figures are given in Table 1, below. It should be noted that the derivation of the equation for Kz neglected any effect due to the variation with depth of the horizontal cross-sectional areas. This neglect will lead to overestimates of Kz.

TABLE 1. DIFFUSION COEFFICIENTS FROM PROPERTY CONTOURS

Property used for the calculations	Date of mean point P	Depth of mean point P (m)	ΔS (ppt)	Δt (days)	δz_+ (m)	δz_- (m)	Δz (m)	K_z (cm^2/sec)
Salinity	June 24/68	65	0.2	21	10	5	19	1.4
"	Dec. 2/68	70	0.2	44	13	11	30	5.7
"	May 1/68	108	0.1	50	24	9	25	1.3
"	Dec. 30/68	110	0.1	46	20	6	30	1.2
"	Feb. 10/68	165	0.02	37	26	19	45	10.4
"	Dec. 28/72	50	0.2	48	25	13	54	4.3
"	Jan. 9/73	50	0.2	20	10	8	20	4.7
DO	Jan. 21/68	120	1.0 ppm	32	38	30	79	$<$ 41.8
"	Jan. 31/68	75	1.0 ppm	31	32	14	44	$<$ 5.6
"	Feb. 20/68	80	1.0 ppm	57	14	9	25	$<$ 1.4

It is also of some interest to determine a diffusion coefficient from the long-term time series for DO, given in Figure 5, to see if a reasonable order-of-magnitude value is obtained from the constant-slope lines which were arbitrarily drawn through the data points. The assumption is made that the change in the time series is due entirely to diffusion, without regard to oxidation, so the value obtained is an upper bound on K_z. Given any pair of lines, for depths z_1 and z_2, on an S-t plot, their slopes are $\frac{\partial S}{\partial t} = \frac{dS}{dt} = \frac{\Delta S}{\Delta t}$, since the depth does not vary along a particular line. Also, $\frac{\partial S}{\partial t} \neq$ fn. (z), since each curve has the same constant slope. The diffusion equation can thus be integrated over the variable z to give:

$$\frac{\partial S}{\partial t} \cdot z = K_z \frac{\partial S}{\partial z}.$$

Likewise, the variable t is not changing along any vertical line connecting the curves designated for z_1 and z_2. Therefore, $\frac{\partial S}{\partial z} = \frac{dS}{dz} = \frac{\Delta S}{\Delta z}$. Since $\Delta z = z_2 - z_1$ and $z = (z_2 + z_1)/2$, one obtains:

$$K_z = \frac{z_2^{\,2} - z_1^{\,2}}{2\ \Delta t}$$

where Δt is the horizontal distance between the pair of lines on the S-t plot. It is apparent that, in this case, K_z must increase with depth. This conforms with the tendency shown by Gade's determinations of K_z in some Norwegian fiords, based on salinity (Gade, 1970). Some results obtained by applying the method to Figure 5 are given in Table 2. On the whole, the values are not unreasonable. However, it should be remembered that these are, in effect, long-term averages.

TABLE 2. DIFFUSION COEFFICIENTS FROM TIME SERIES

Property used for the calculations	Date	Mean Depth (m)	Δt (months)	z_1 (m)	z_2 (m)	K_z (maximum) (cm^2/sec)
DO	1960	125	10	100	150	2.4
"	"	150	22	100	200	2.6
"	"	175	11	150	200	3.1
"	1963	125	1	100	150	24.1
"	1964	175	2.5	150	200	13.5
"	1968	125	11.5	100	150	2.1
"	"	150	18.5	100	200	3.1
"	"	175	6.5	150	200	5.2

CONCLUSION

It is apparent that the basin water in Howe Sound is subject to occasional renewal by influxes of water over the sill. Indeed, the influx of water to a depth of 100 meters or so is a frequent enough occurrence that renewal to this depth can perhaps be described as 'almost continuous'. Renewal of the very deep basin water appears to occur at least every few years. After an exchange of major proportions, the basin water is nearly homogeneous in all of its properties and has the same characteristics as the outside water which was flowing in over the sill. Thus, it could happen that the DO level in the basin may not increase appreciably at the time of an influx, depending on the relative concentrations of the incoming and resident waters. Generally, however, the DO level is increased during the process. The density of the basin water is highest just after an exchange and is subsequently reduced by diffusion.

The "triggering" mechanism for the renewal process appears to be associated with a strong outflowing of surface water over the sill. The strong seaward flow apparently induces a sub-surface replacement flow across the sill of relatively dense "outside" water. The depth to which renewal of the basin water takes place depends on the density of the replacement water. The principal causes of a strong surface outflow are high down-channel winds and heavy fresh water run-off. The former often occurs in conjunction with widespread cold air masses in wintertime; the latter may result from river freshet

or anomalously high rainfall. Since deep water of the greatest density seems to occur outside of the sill in the wintertime, renewal of the very deep basin water tends to be associated with strong winter winds. High run-offs generally occur at times when the outside water has a density somewhat less than the maximum value. Therefore, exchanges induced at these times may only penetrate to intermediate depths in the basin. The duration of flow into the basin during an exchange probably depends on the intensity of the seaward surface flow and the relative densities of water at various depths on either side of the sill. The data show that major changes in water structure can occur over periods not exceeding a month, and perhaps much less.

The occurrence of renewal is quickly and easily determined from plots of salinity or DO *vs.* time, with depth as a running parameter. A better indication of the magnitude of the replacement over depth may be obtained from contoured plots of the vertical distribution of salinity or density *vs.* time for a section along the axis of the sound. The major deep water exchanges can probably be monitored with a sampling interval of about six months. To monitor all of the exchanges of consequence, a monthly sampling interval is required. However, to observe these exchanges in some detail, a much smaller sampling interval appears to be necessary. Likewise, the property changes engendered by the major renewals are of sufficient magnitude to be reliably observed by STD systems using paper chart recorders. To be certain of sufficient accuracy to observe all of the renewals of consequence, it is probably necessary to use

an STD system having a facility for digital magnetic tape recording, or to obtain actual samples for laboratory analysis.

Because the character of the influx (i.e. the volume flow rate, penetration depth, and flow duration), and the properties of the replacement water, depend in large measure on the properties of the water lying seaward of the sill, insight into the nature of the exchanges may be assisted by a better understanding of the processes occurring in the Strait of Georgia.

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Figure 1. Howe Sound, showing the location of sampling stations and the sill.

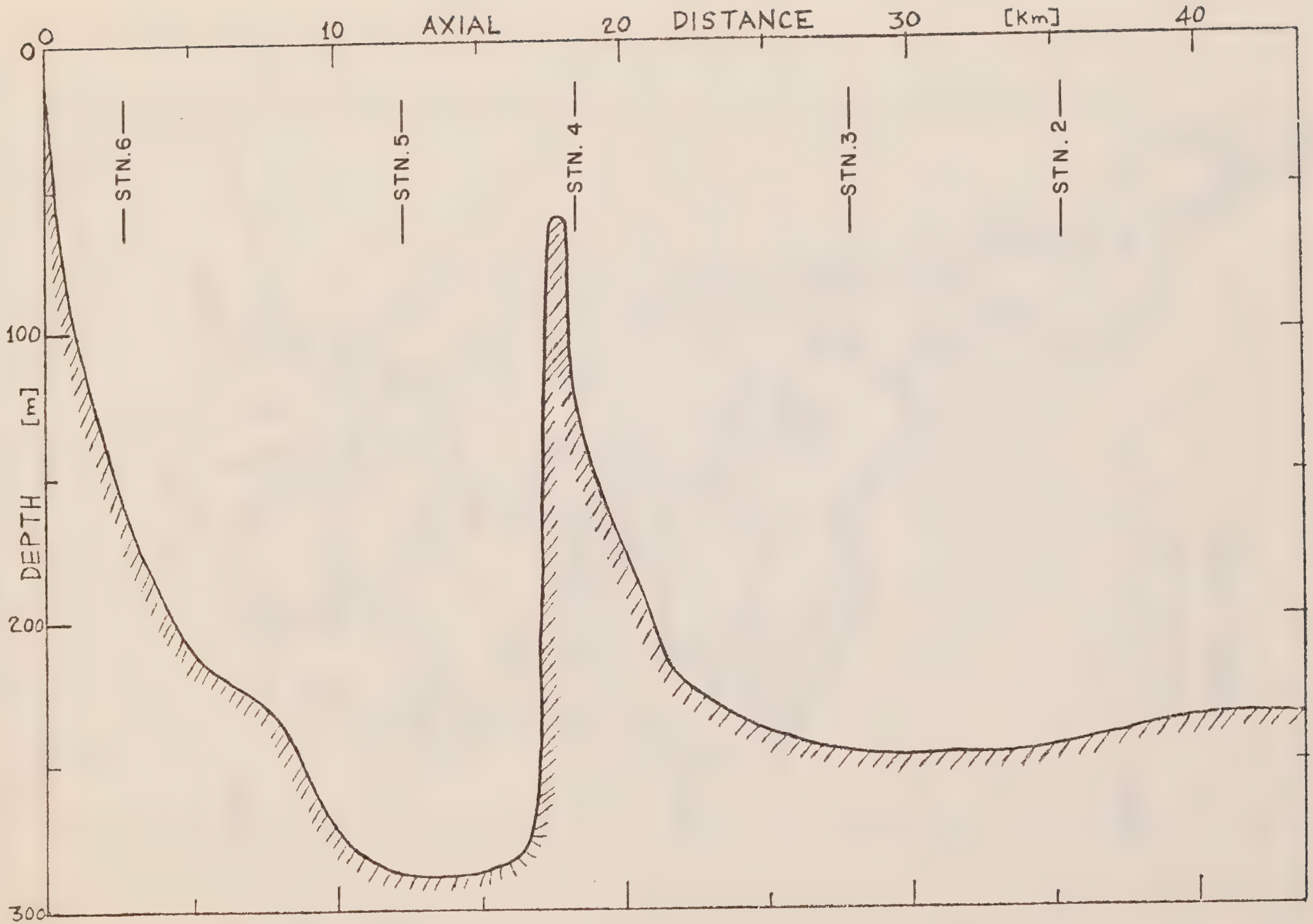

Figure 2. Axial section along the main channel of Howe Sound.

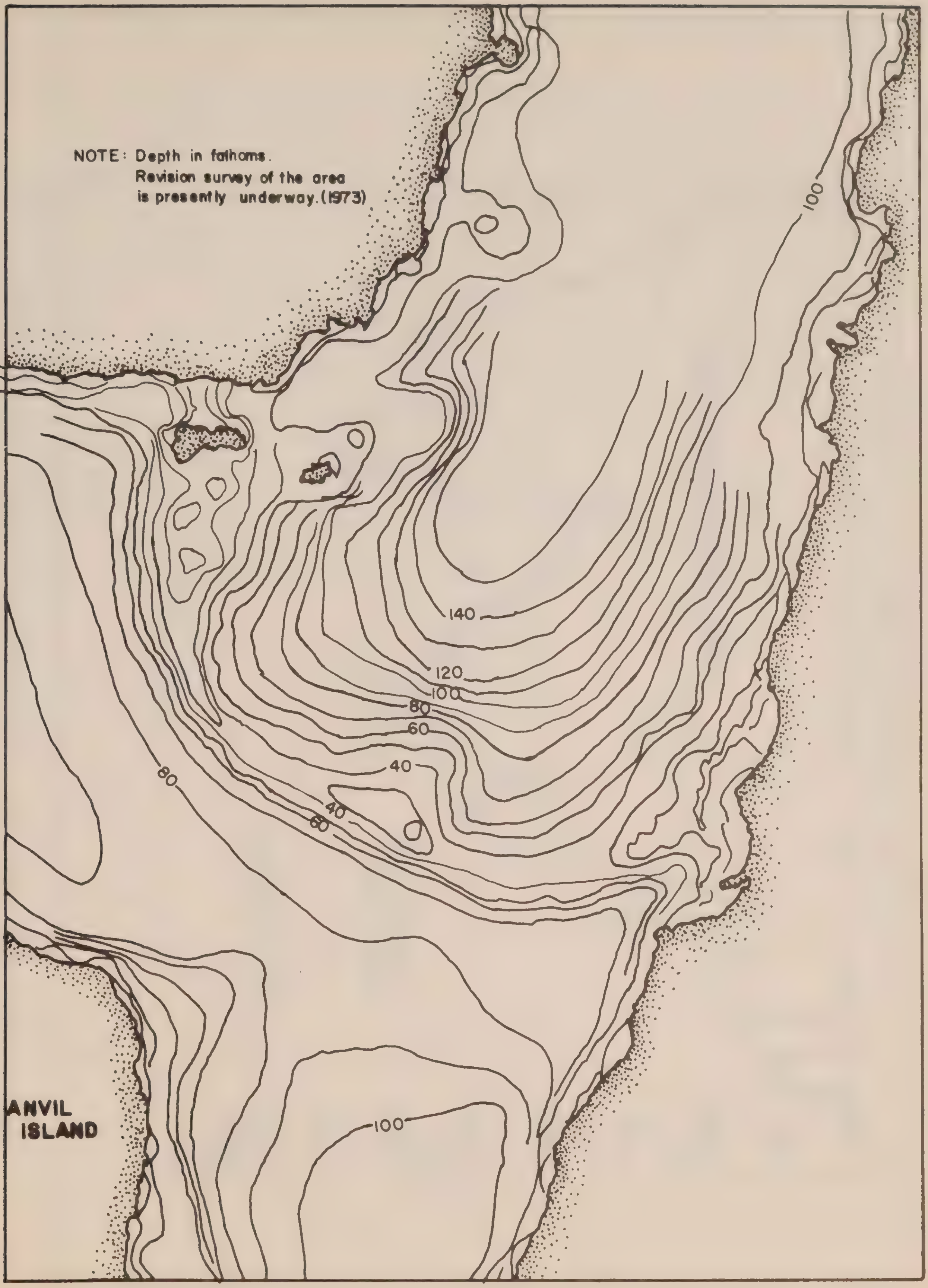

Figure 3. Contours in the vicinity of the sill in Howe Sound.

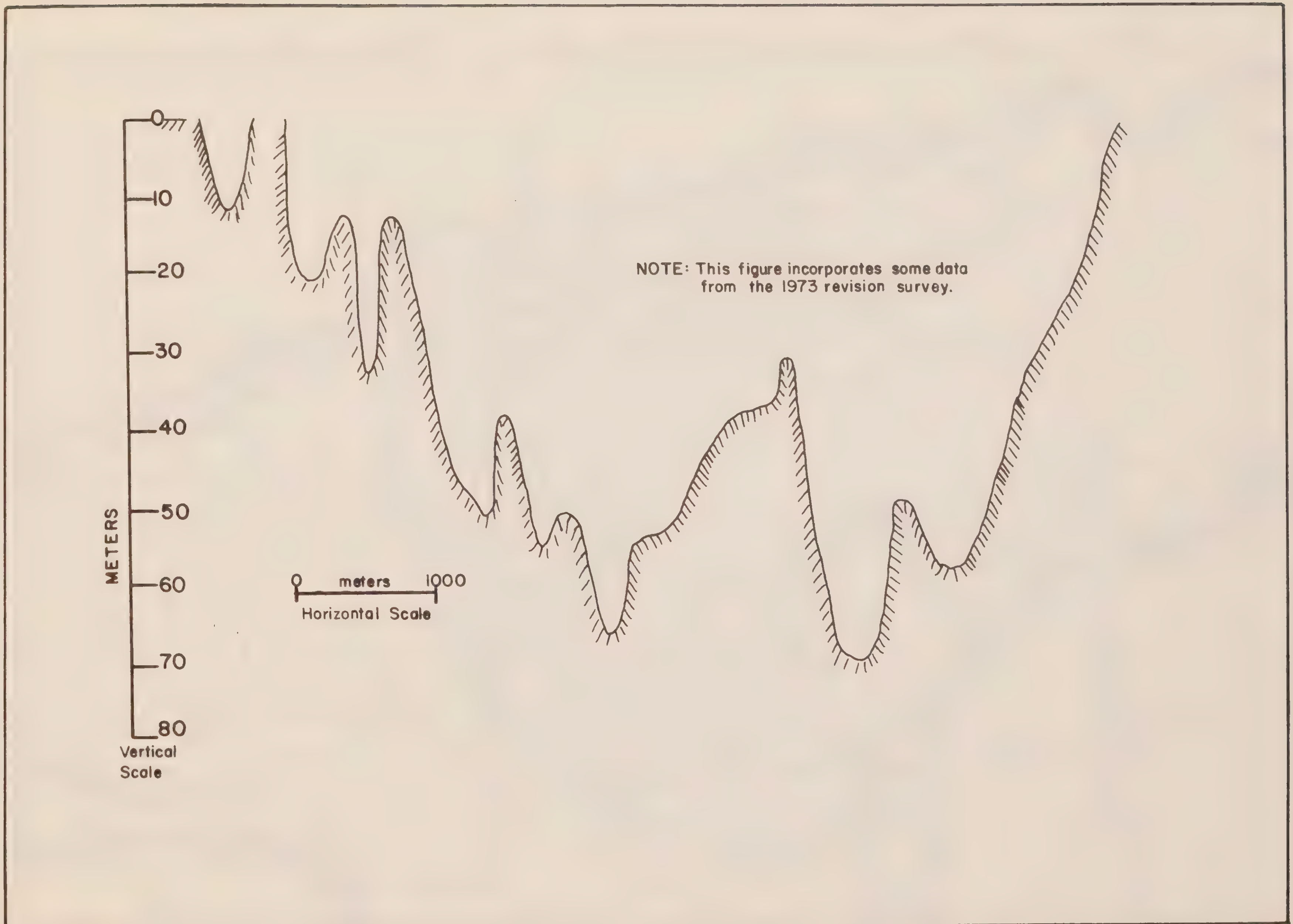

Figure 4. Vertical section along the sill centre line.

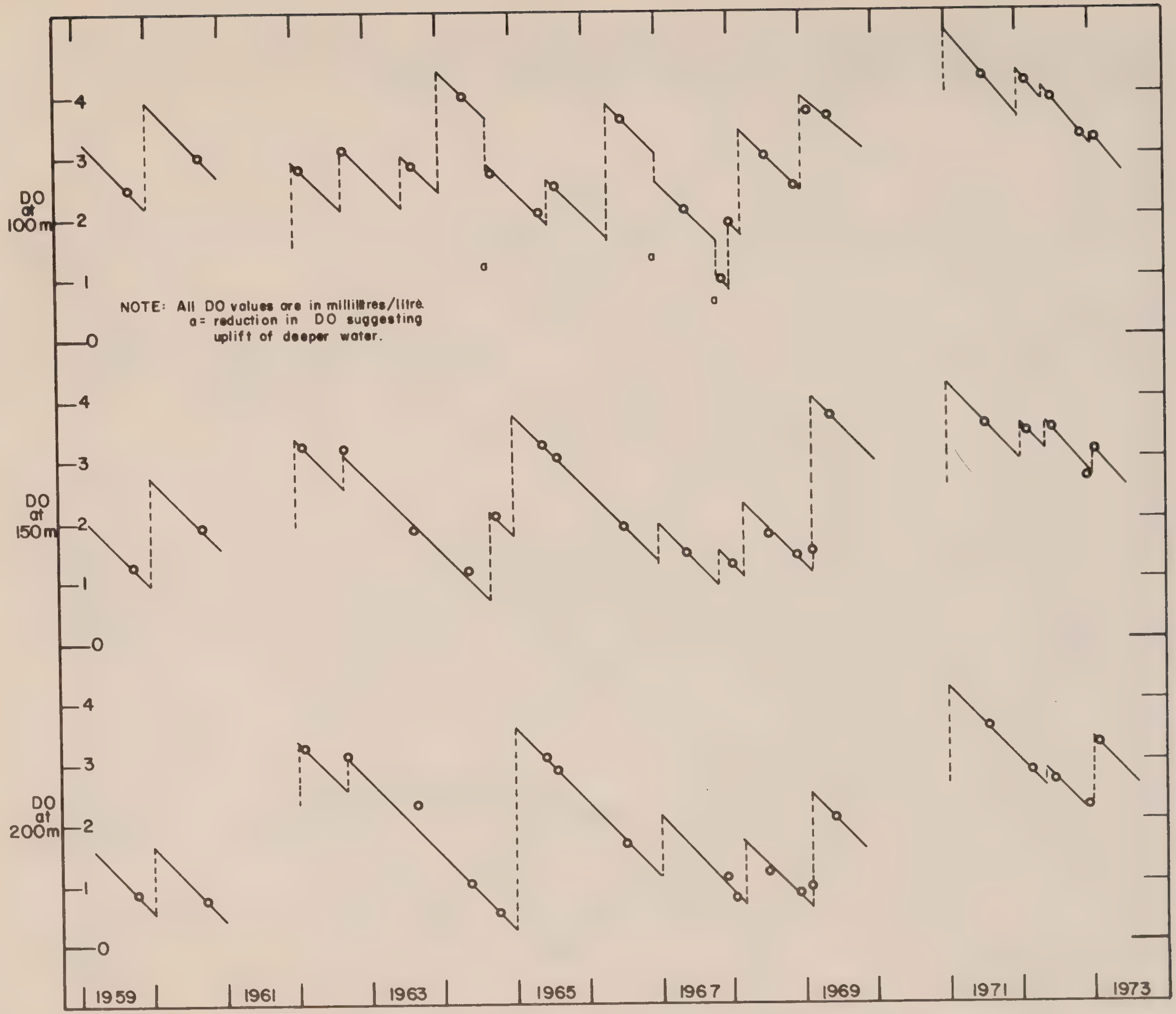

Figure 5. Dissolved oxygen time series, 1959-73, for three depths near Stn. 5.

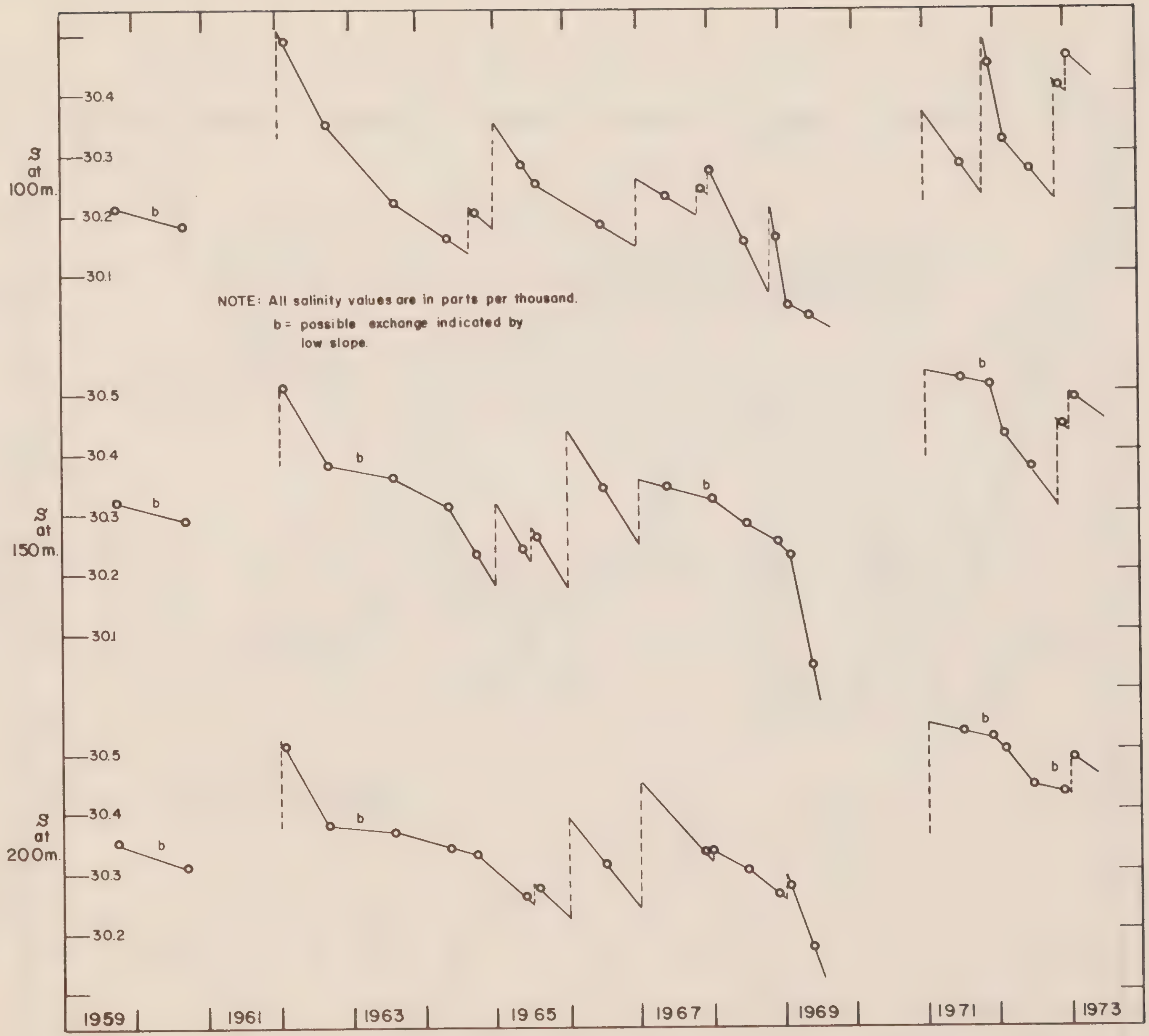

Figure 6. Salinity time series, 1959-73, for three depths near Stn. 5.

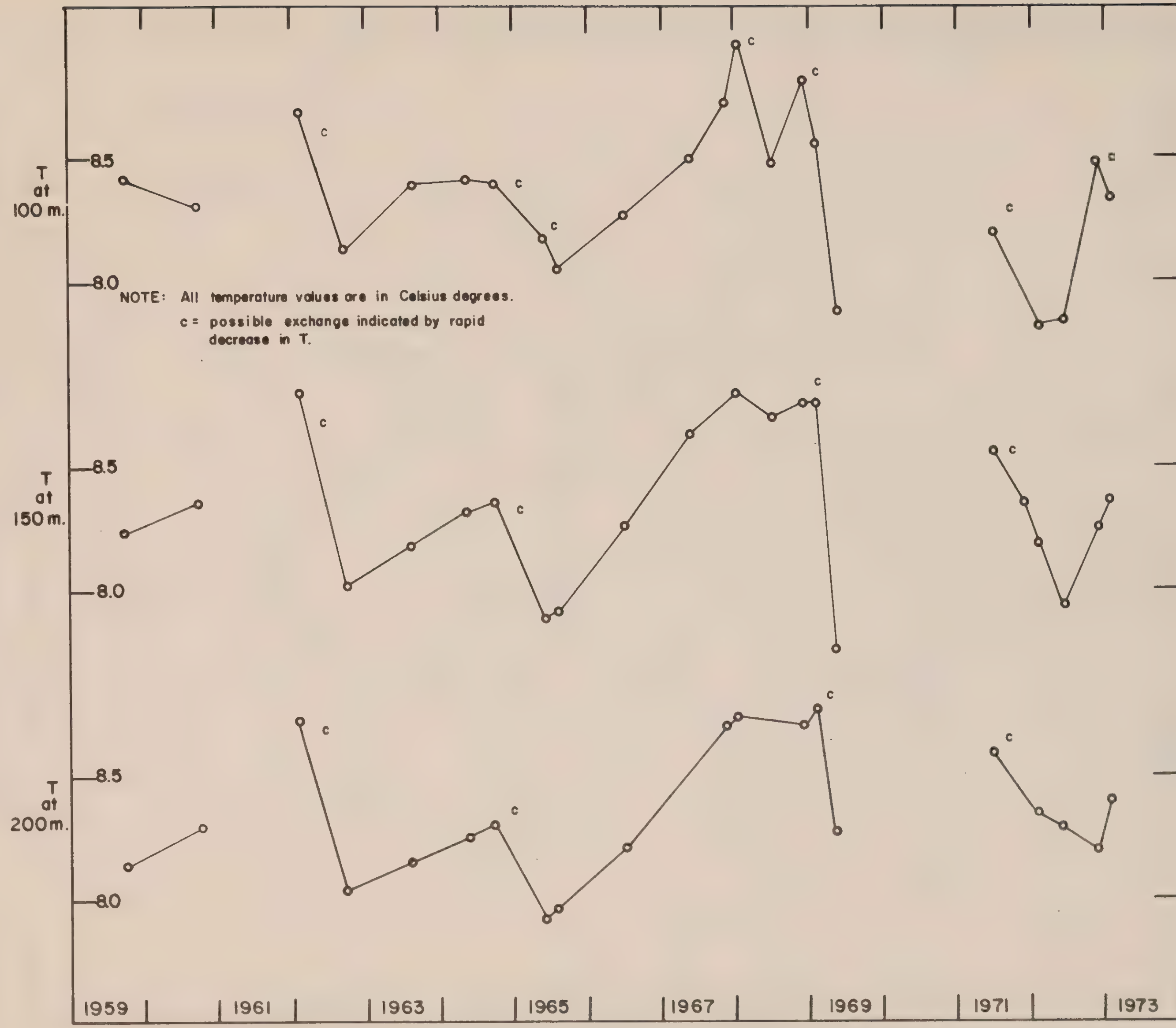

Figure 7. Temperature time series, 1959-73, for three depths near Stn. 5.

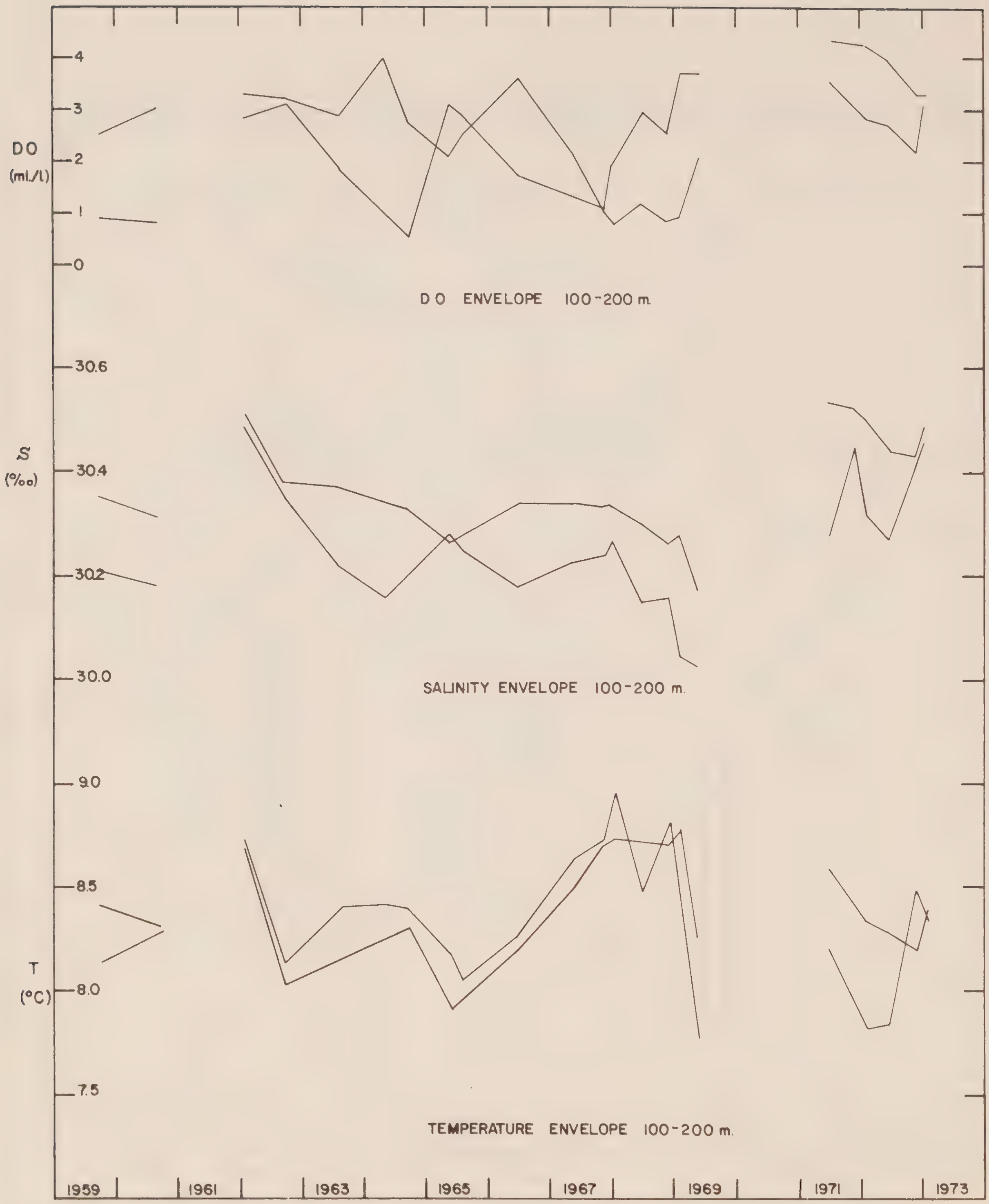

Figure 8. Time series envelopes, 1959-73, for salinity, temperature and dissolved oxygen between depths of 100 and 200 m near Stn. 5.

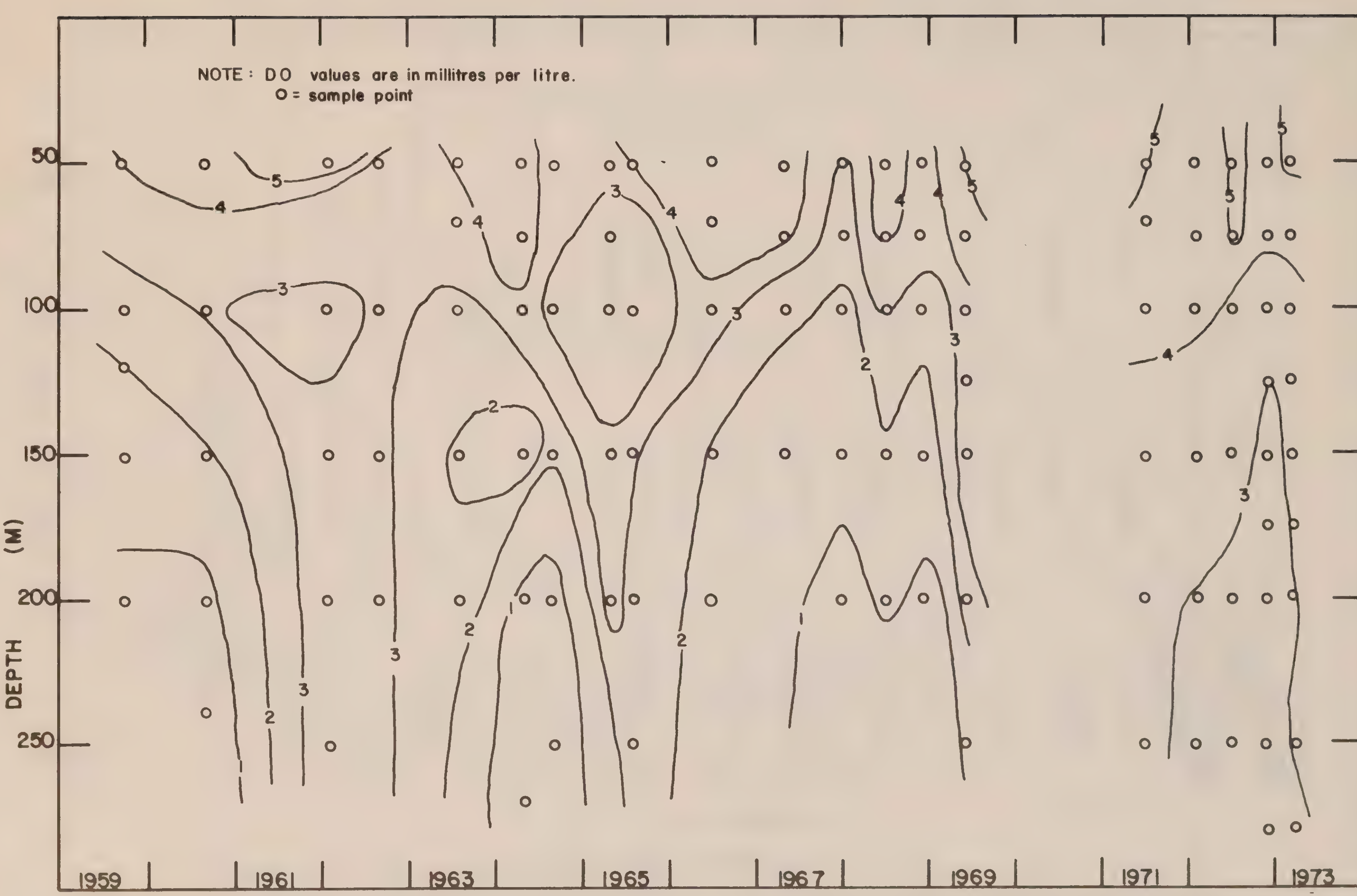

Figure 9. Dissolved oxygen contours near Stn. 5 on a depth-time plot, 1959-73.

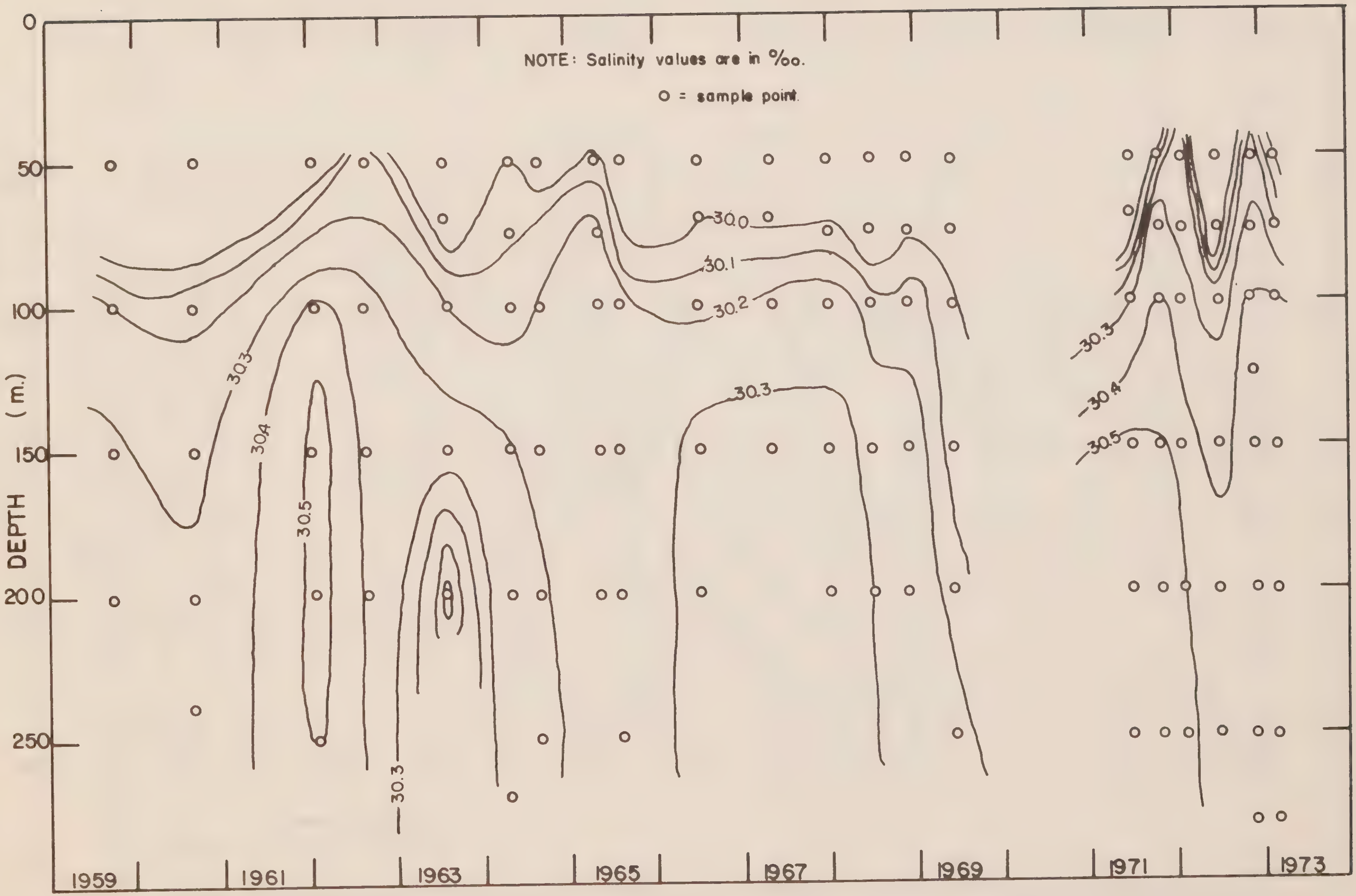

Figure 10. Salinity contours near Stn. 5 on a depth-time plot, 1959-73.

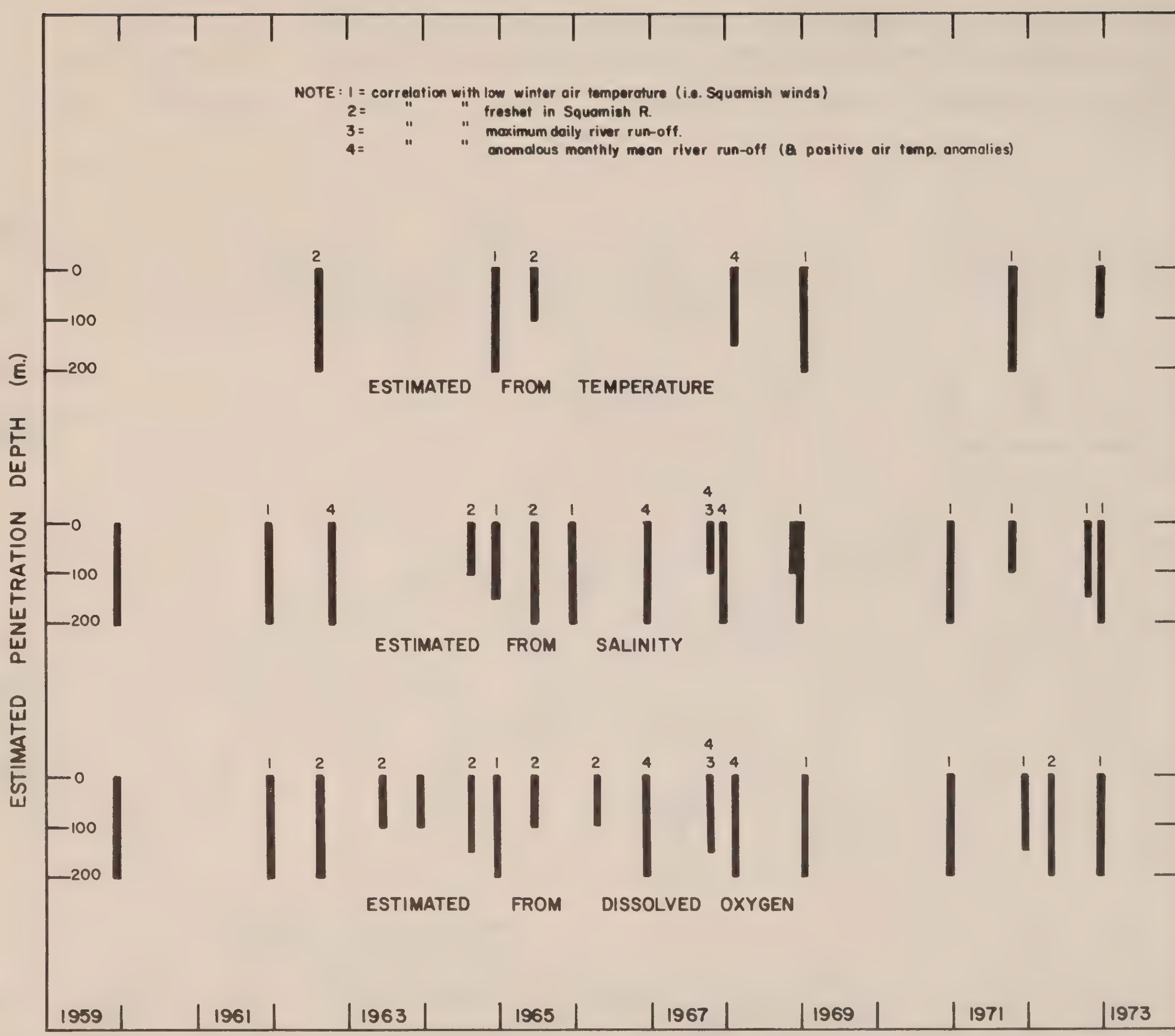

Figure 11. Suggested occurrences of exchanges, 1959-73.

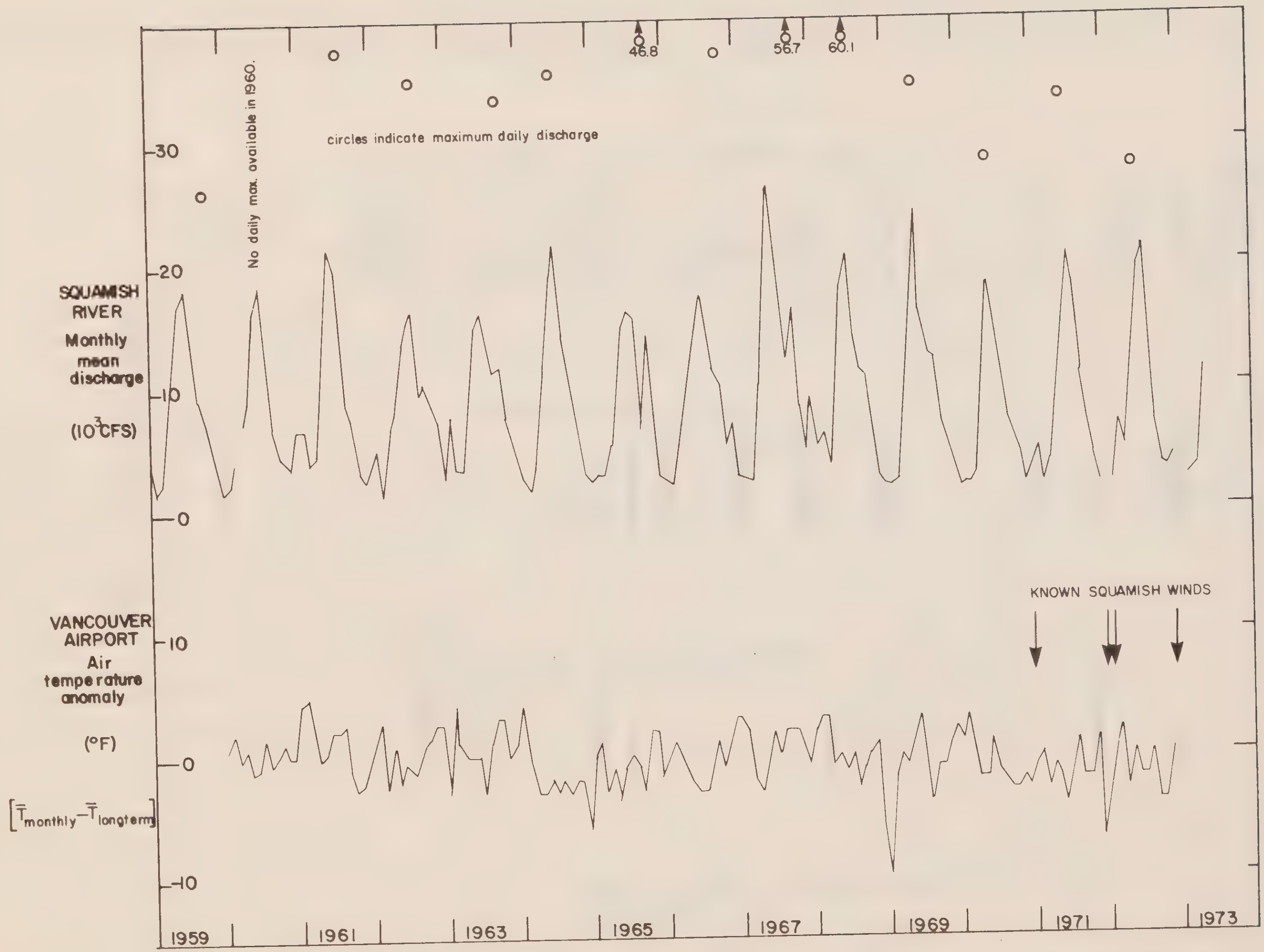

Figure 12. Time series, 1959-73, for the monthly mean discharge from the Squamish River and for the monthly mean air temperature anomaly at the Vancouver International Airport.

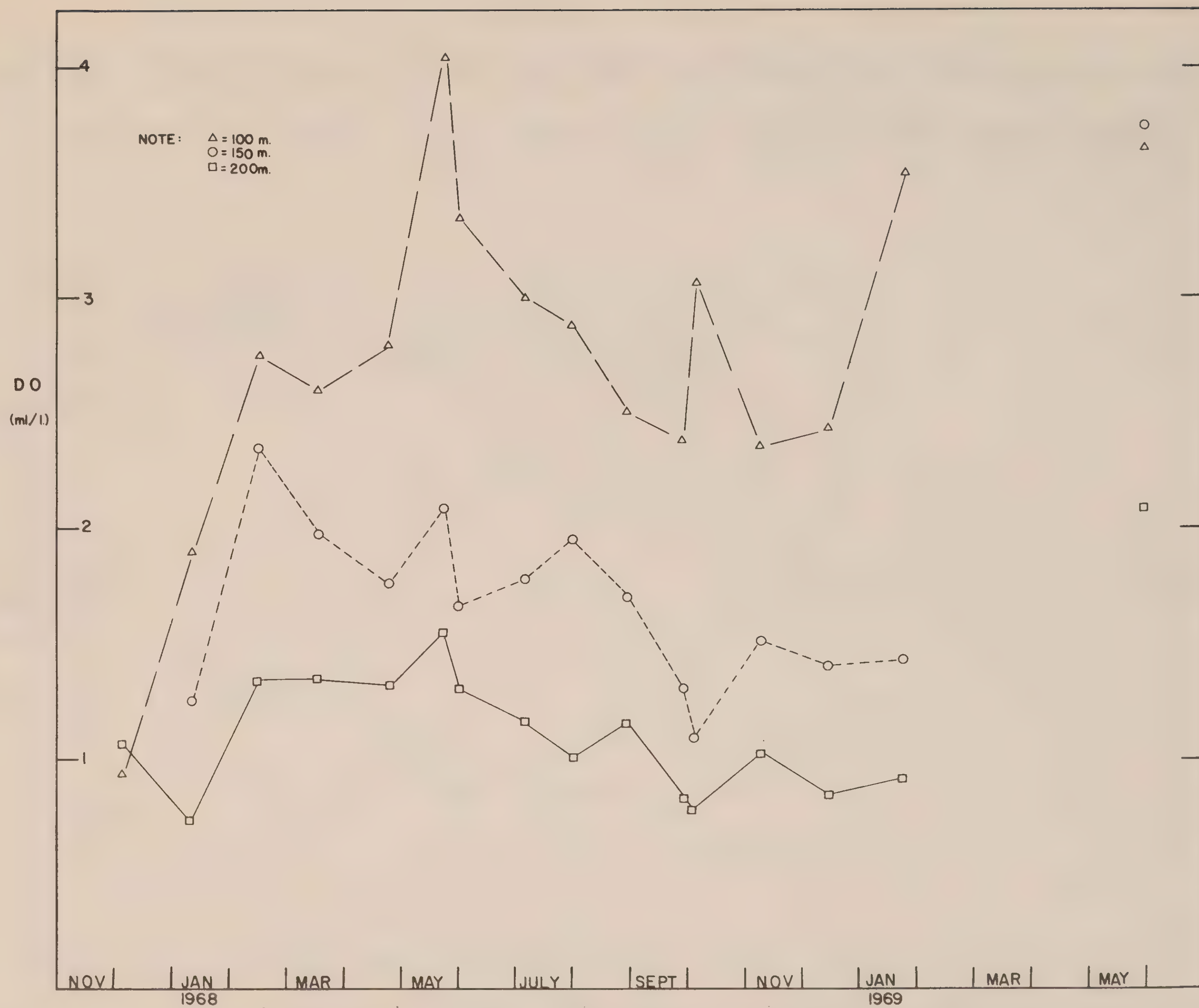

Figure 13. Dissolved oxygen time series, 1968, for three depths near Crean and Ages Stn. 32.

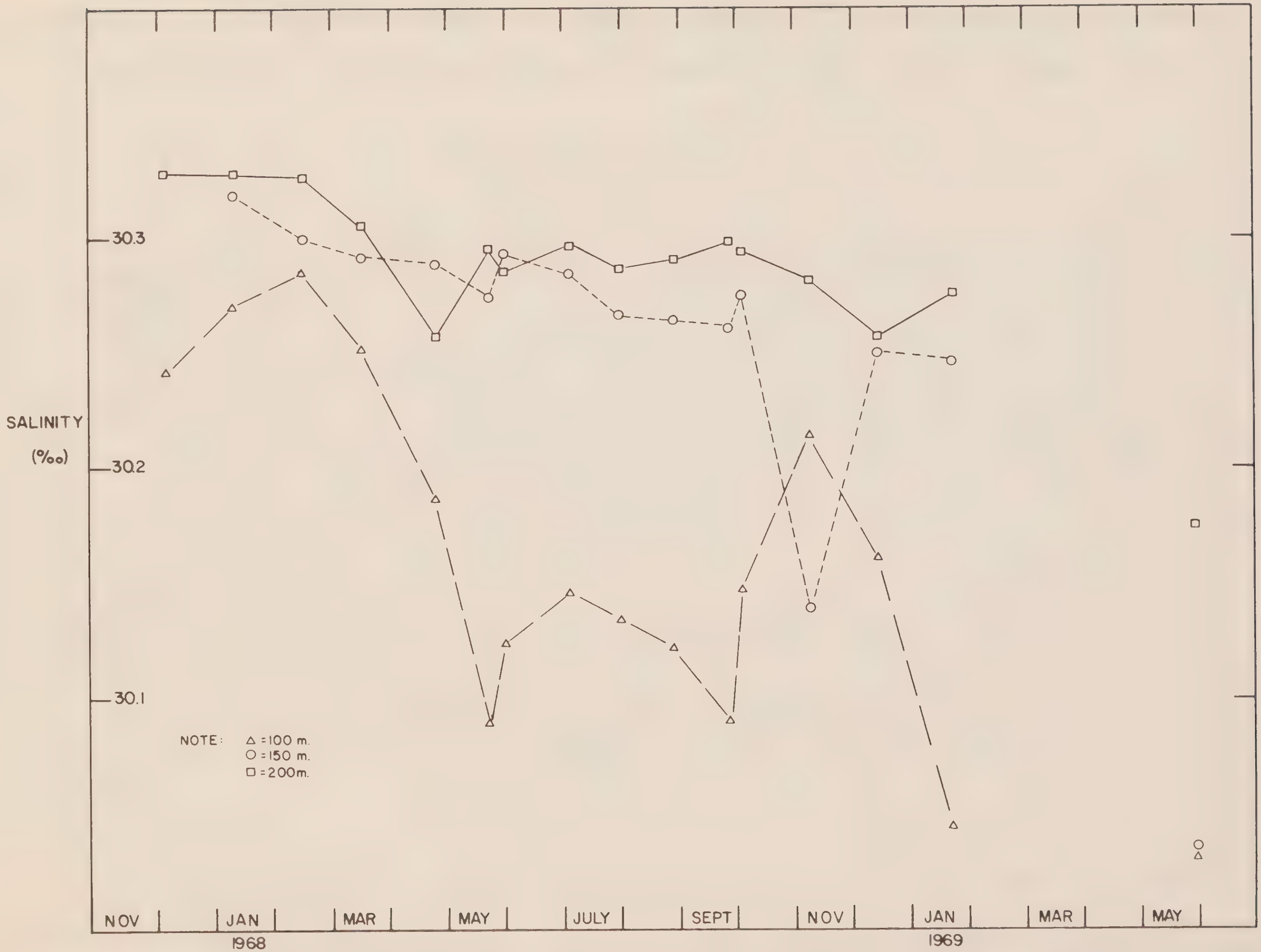

Figure 14. Salinity time series, 1968, for three depths near Crean and Ages Stn. 32.

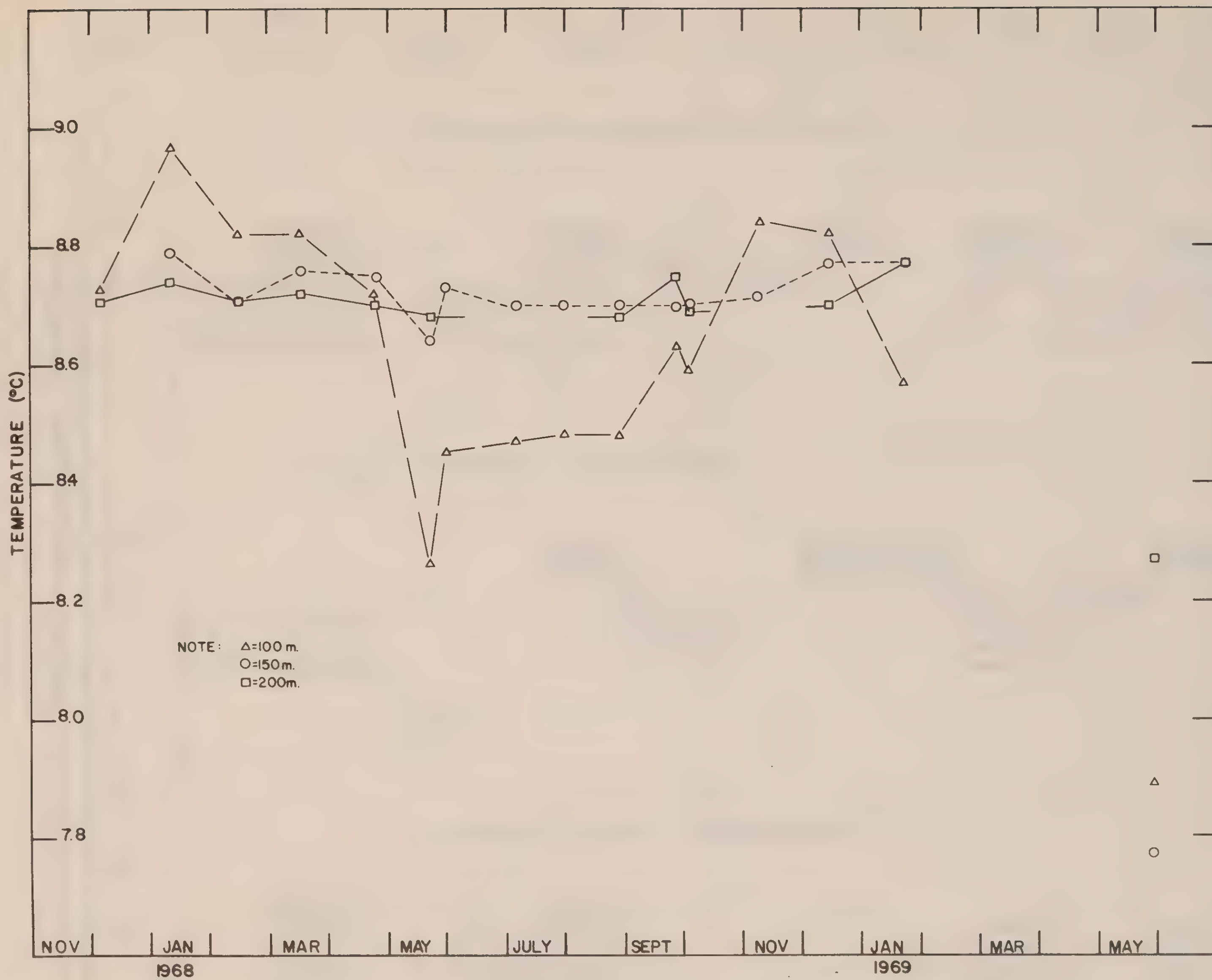

Figure 15. Temperature time series, 1968, for three depths near Crean and Ages Stn. 32.

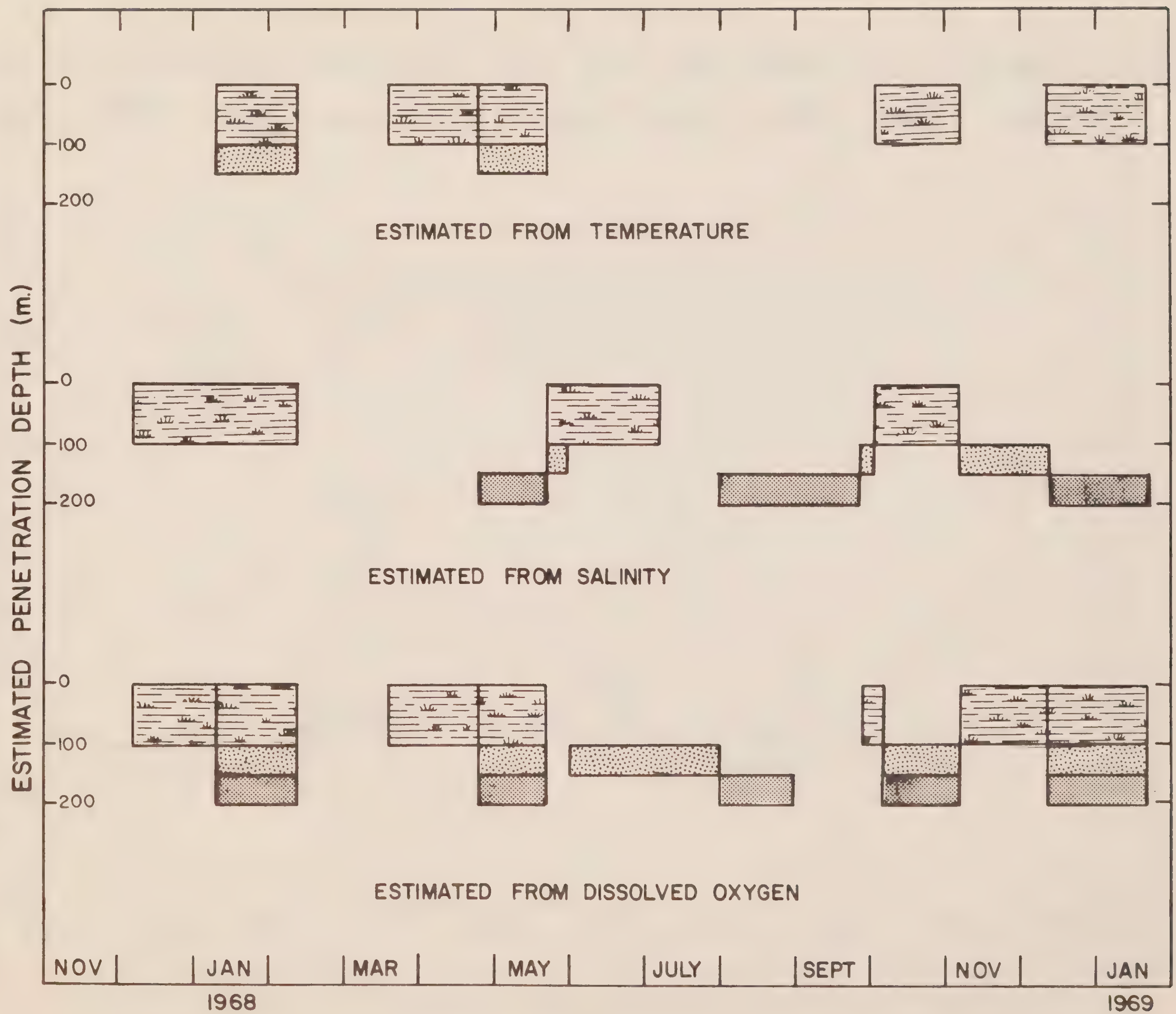

Figure 16. Suggested occurrences of exchanges, 1968.

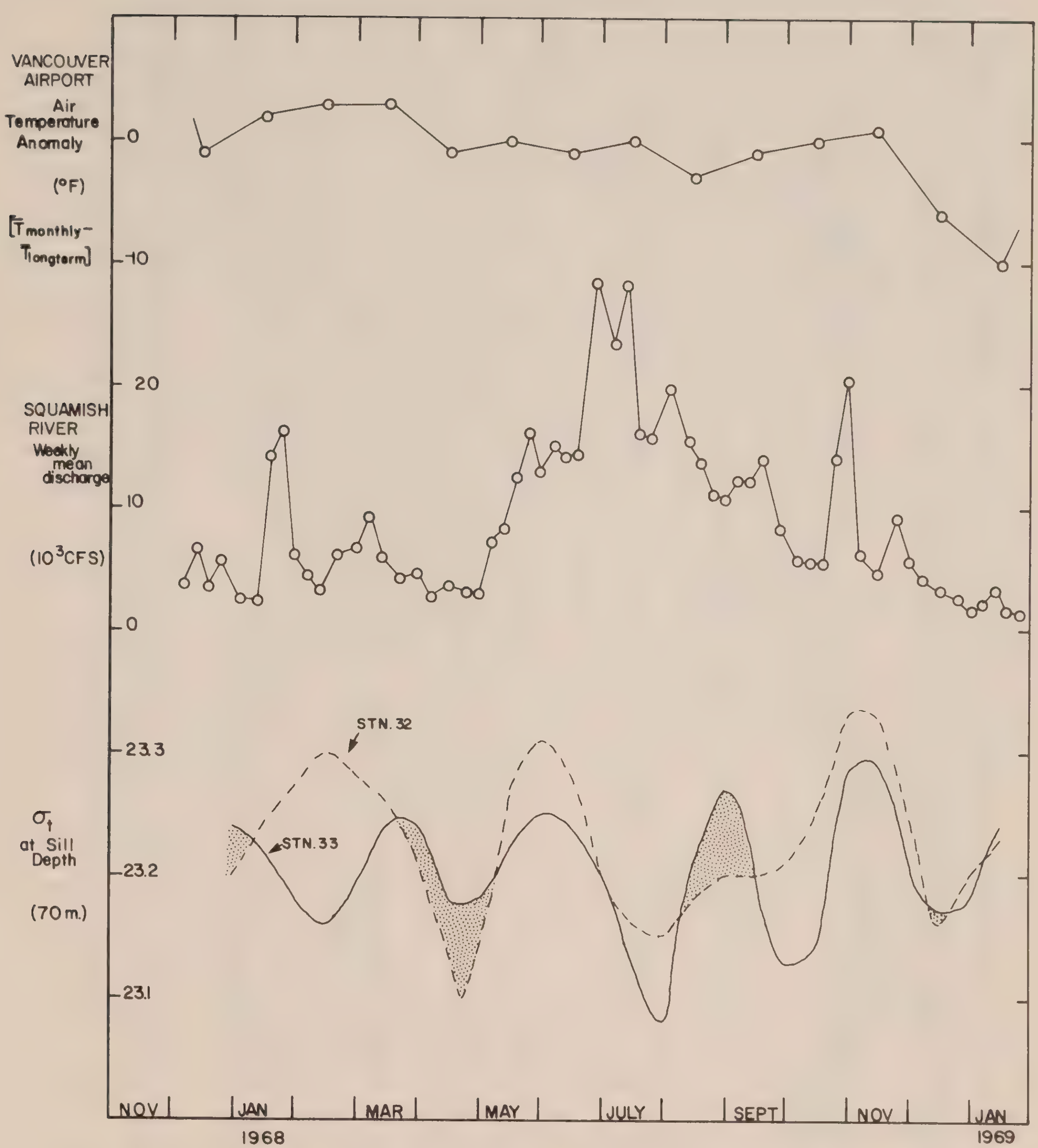

Figure 17. Time series, 1968, for the monthly mean air temperature anomaly at the Vancouver International Airport, for the weekly mean discharge from the Squamish River, and for sigma-t at sill depth for two stations in Howe Sound.

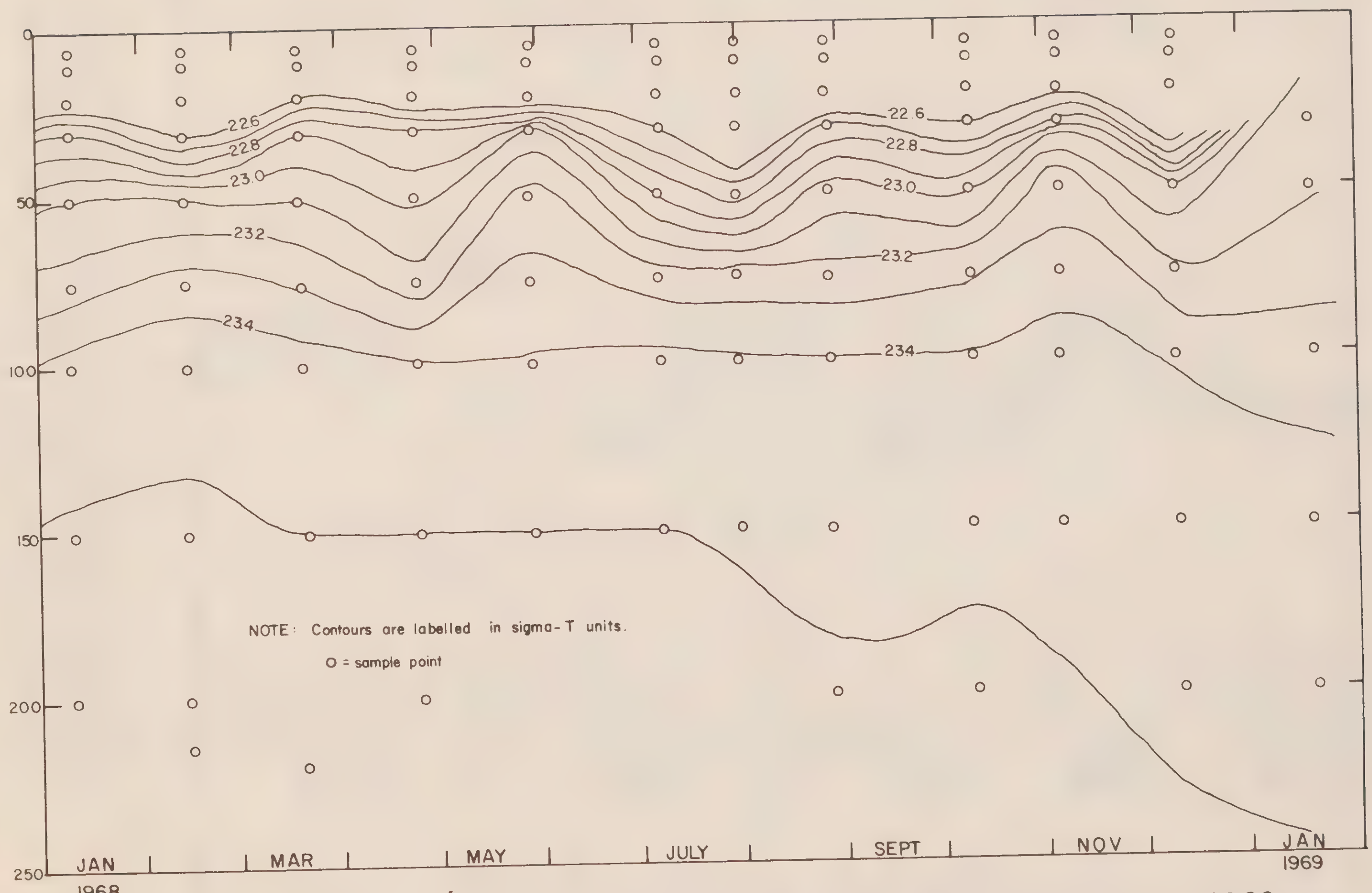

Figure 18. Sigma-t contours near Stn. 32 on a depth-time plot, 1968.

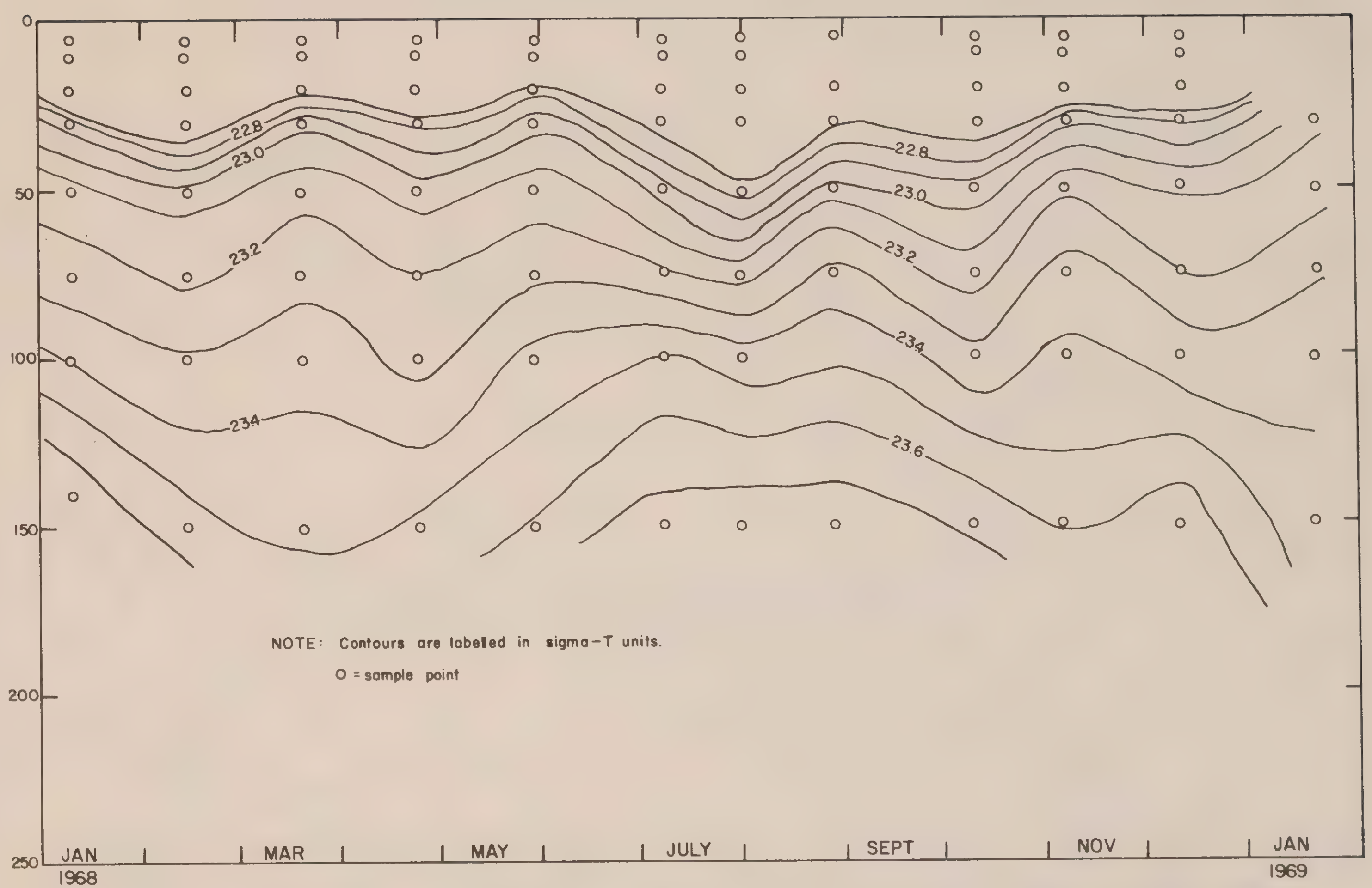

Figure 19. Sigma-t contours near Stn. 33 on a depth-time plot, 1968.

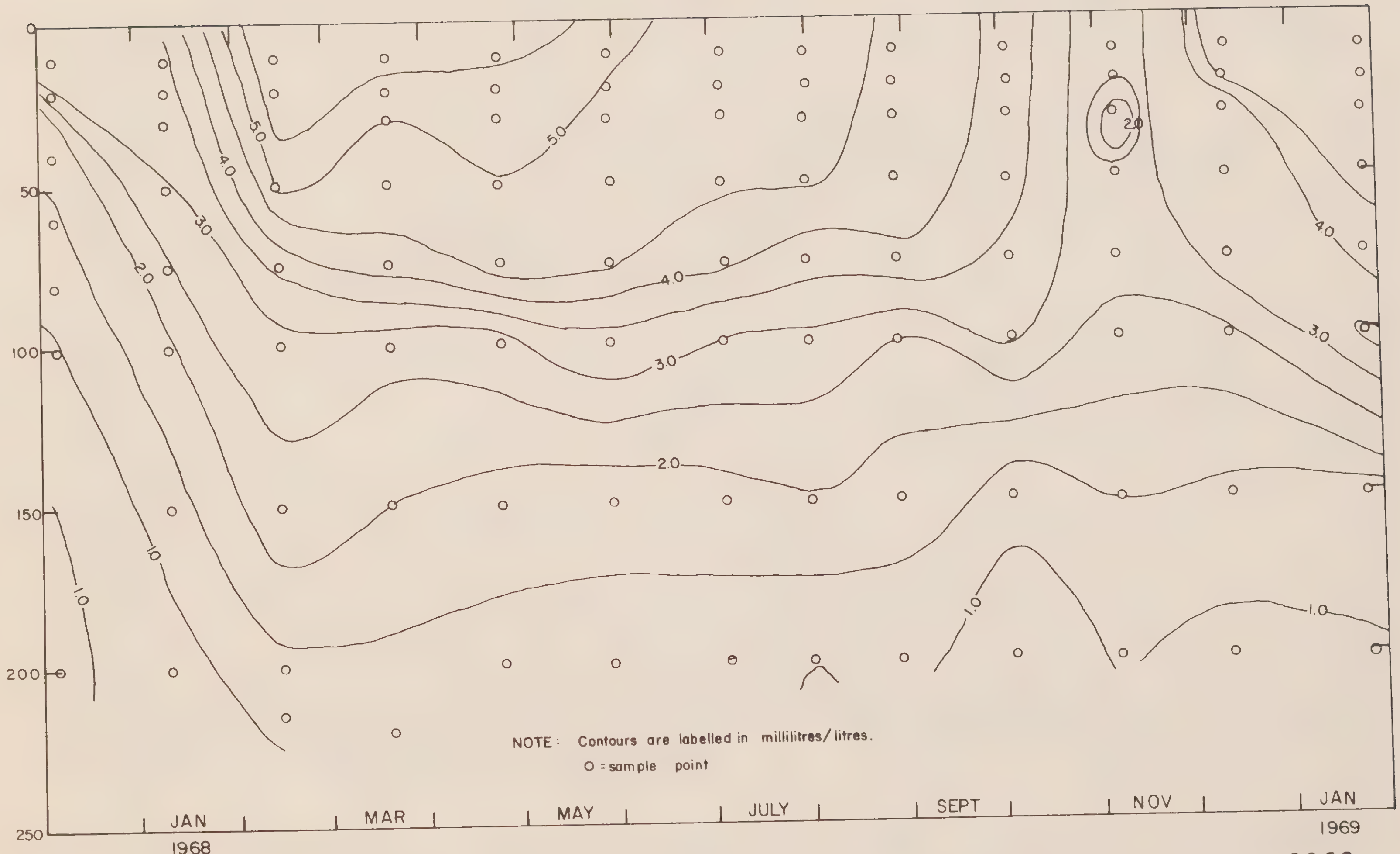

Figure 20. Dissolved oxygen contours near Stn. 32 on a depth-time plot, 1968.

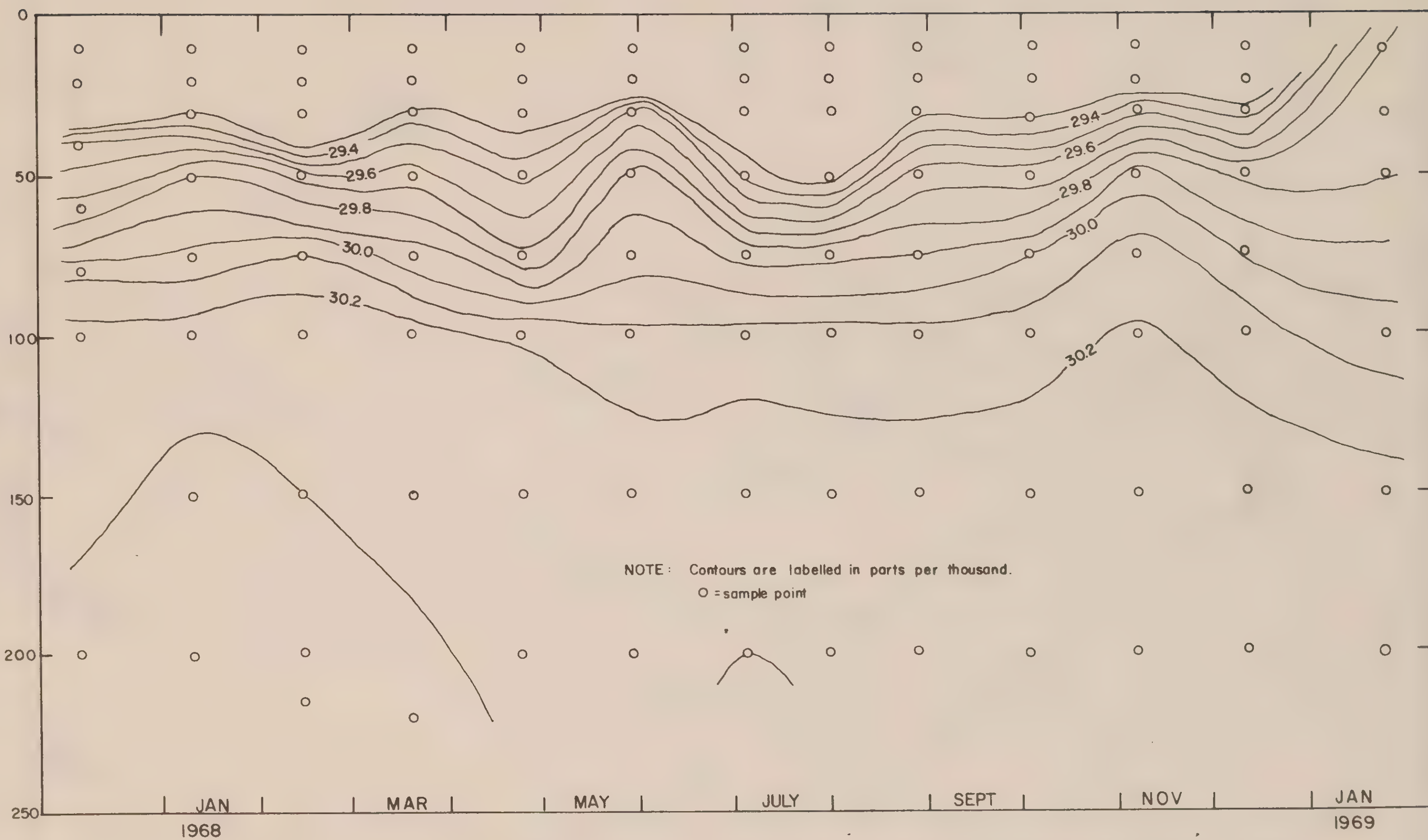

Figure 21. Salinity contours near Stn. 32 on a depth-time plot, 1968.

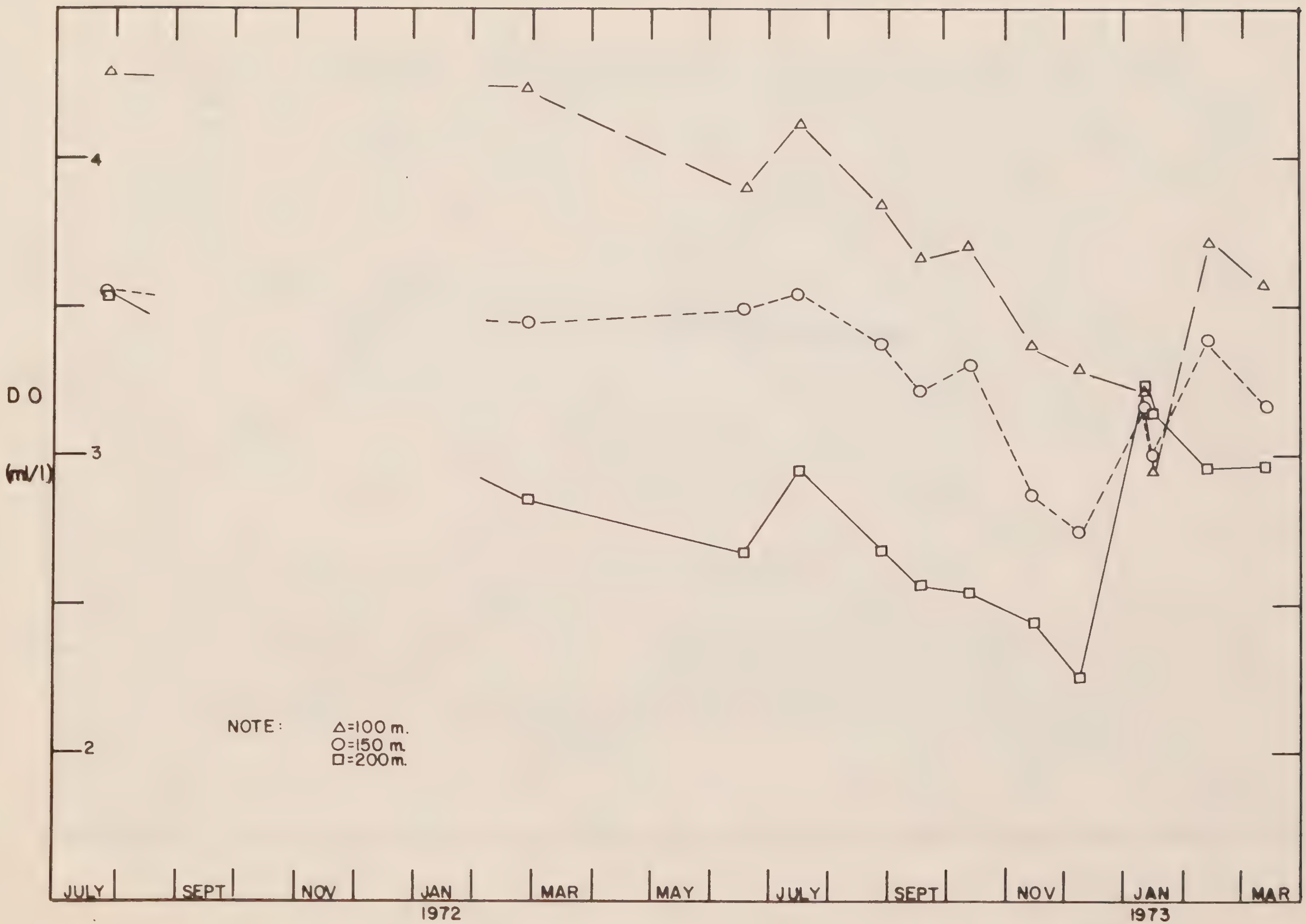

Figure 22. Dissolved oxygen time series, 1971-73, for three depths near Stn. 5.

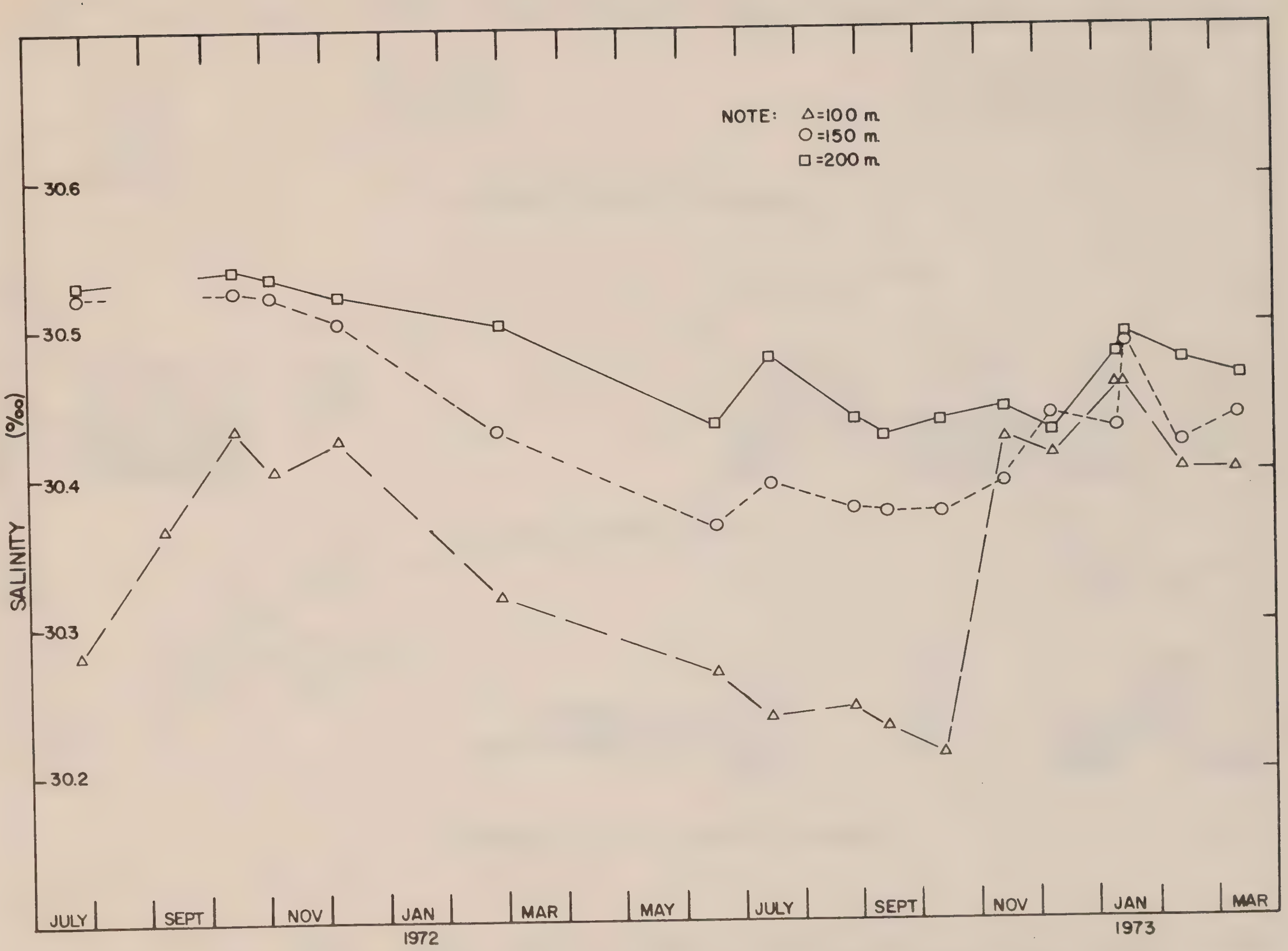

Figure 23. Salinity time series, 1971-73, for three depths near Stn. 5.

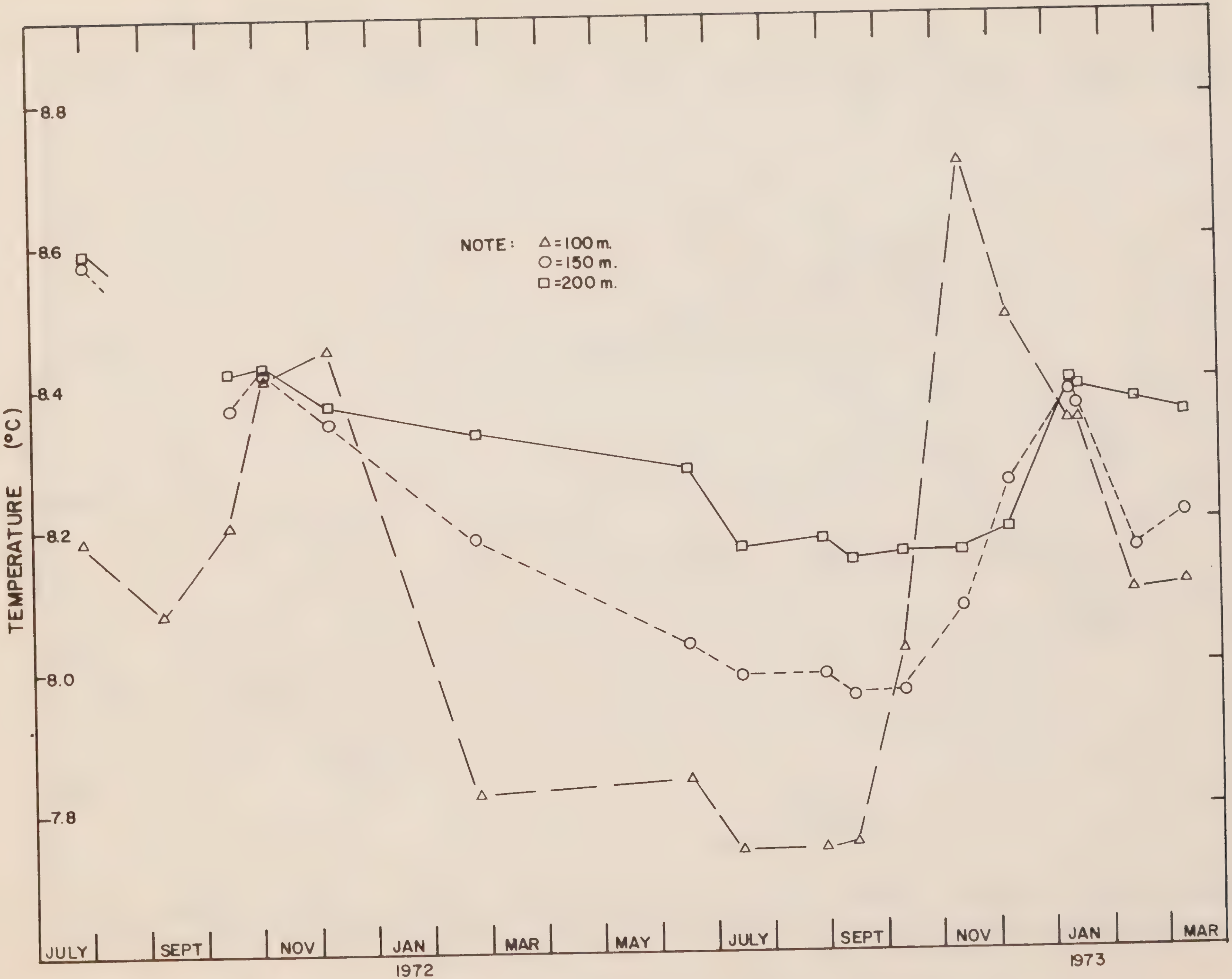

Figure 24. Temperature time series, 1971-73, for three depths near Stn. 5.

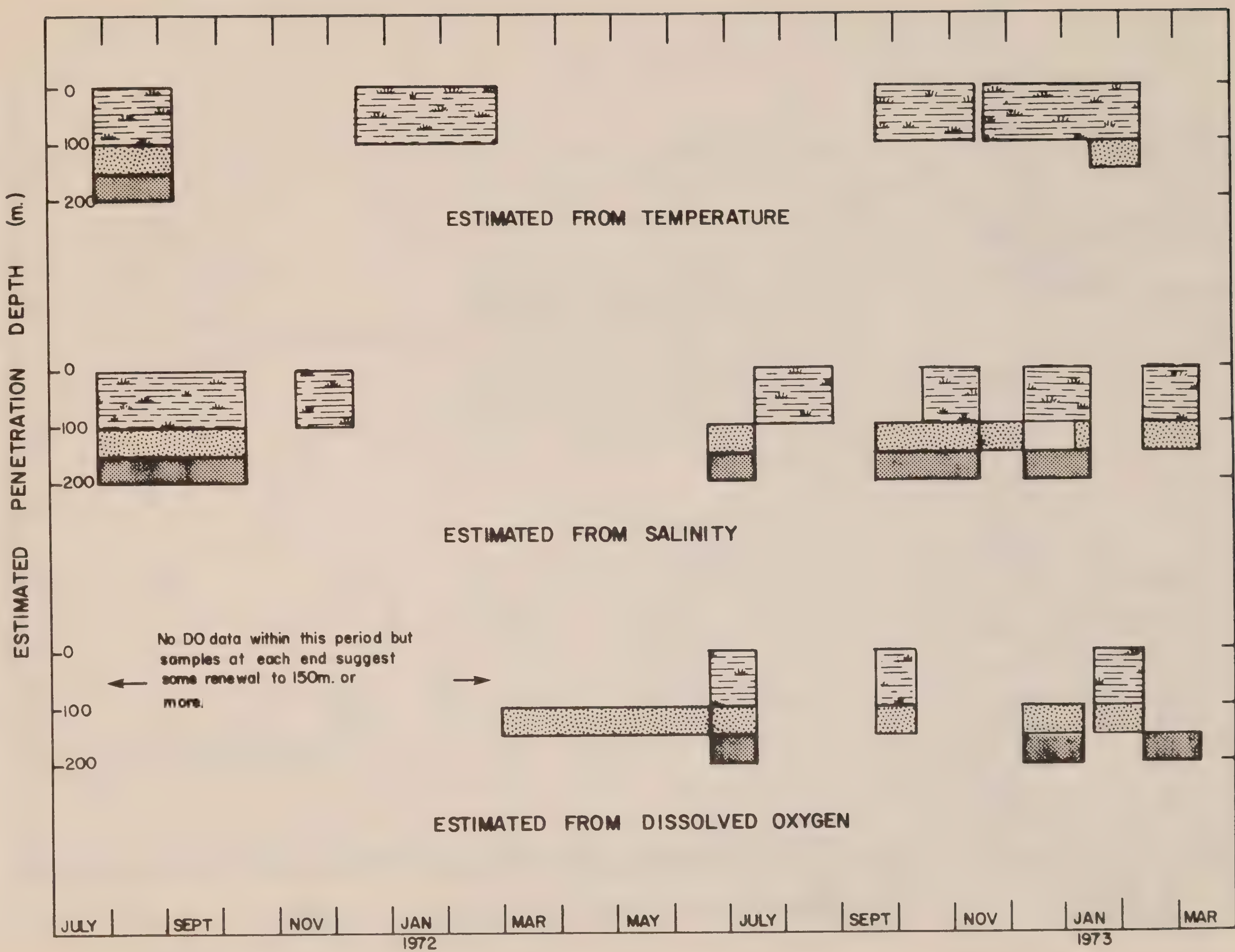

Figure 25. Suggested occurrences of exchanges, 1971-73.

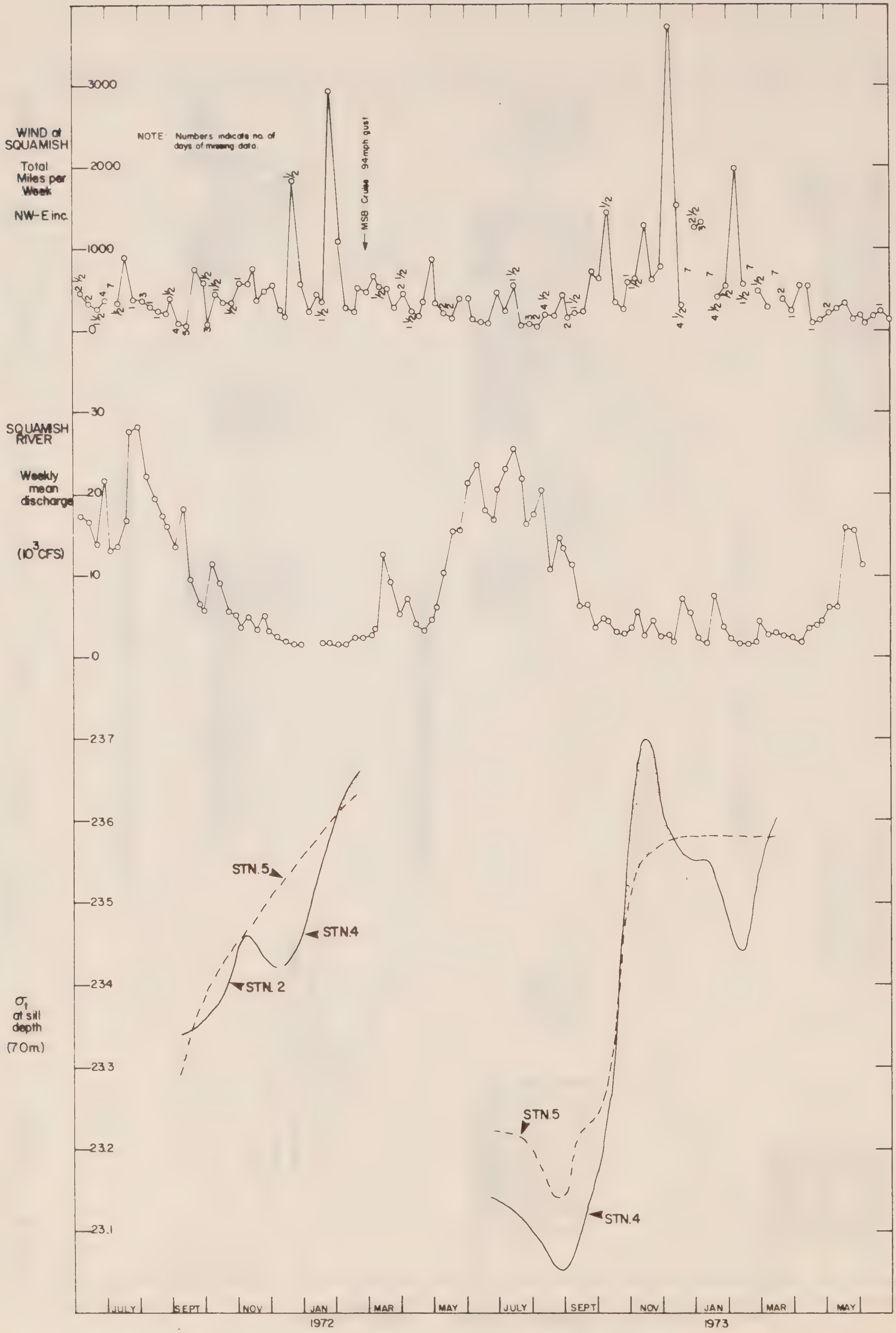

Figure 26. Time series, 1971-73, for the weekly wind mileage in the NW-E sector at Squamish, for the weekly mean discharge from the Squamish River, and for sigma-t at sill depth for two stations in Howe Sound.

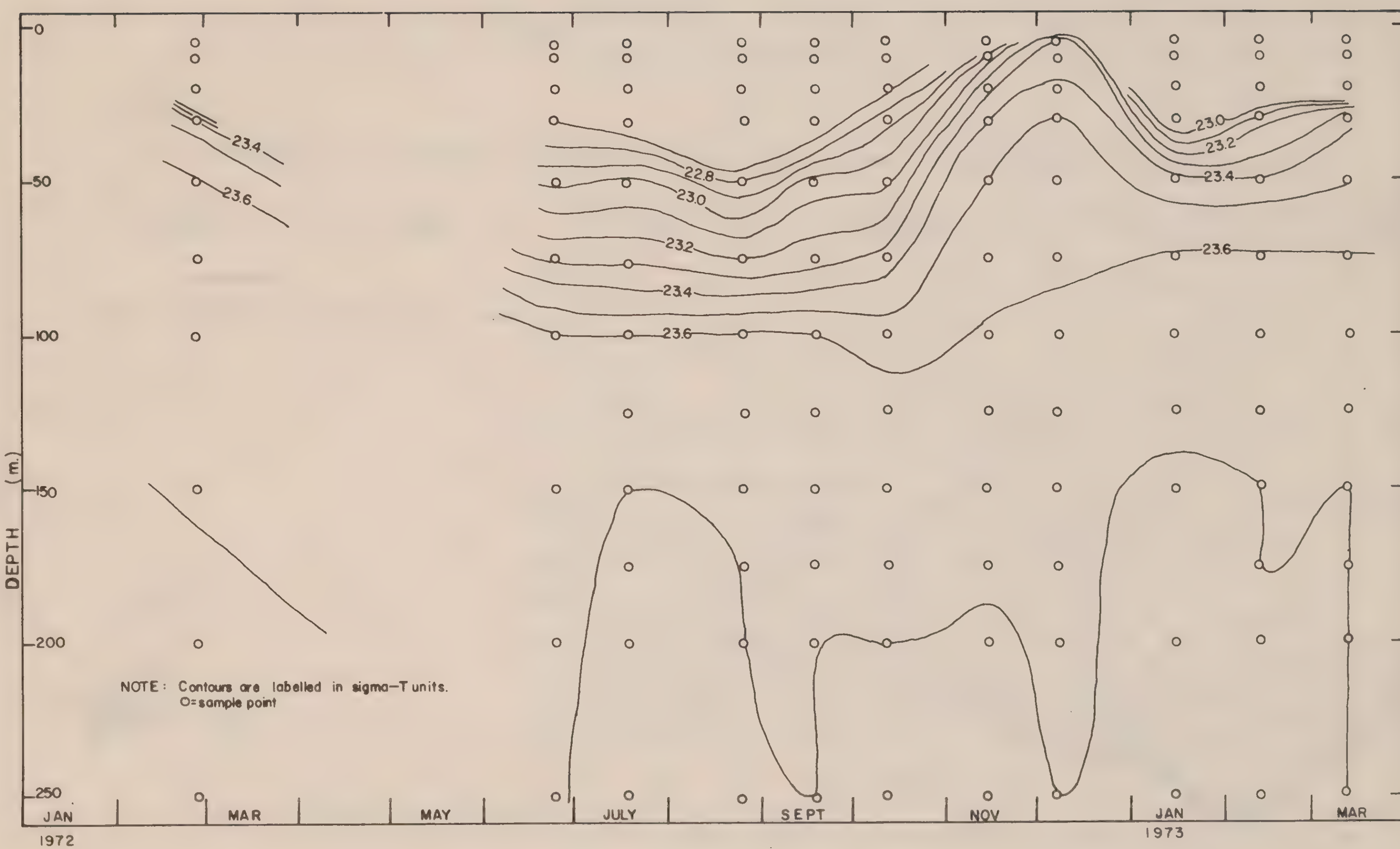

Figure 27. Sigma-t contours near Stn. 5 on a depth-time plot, 1972-73.

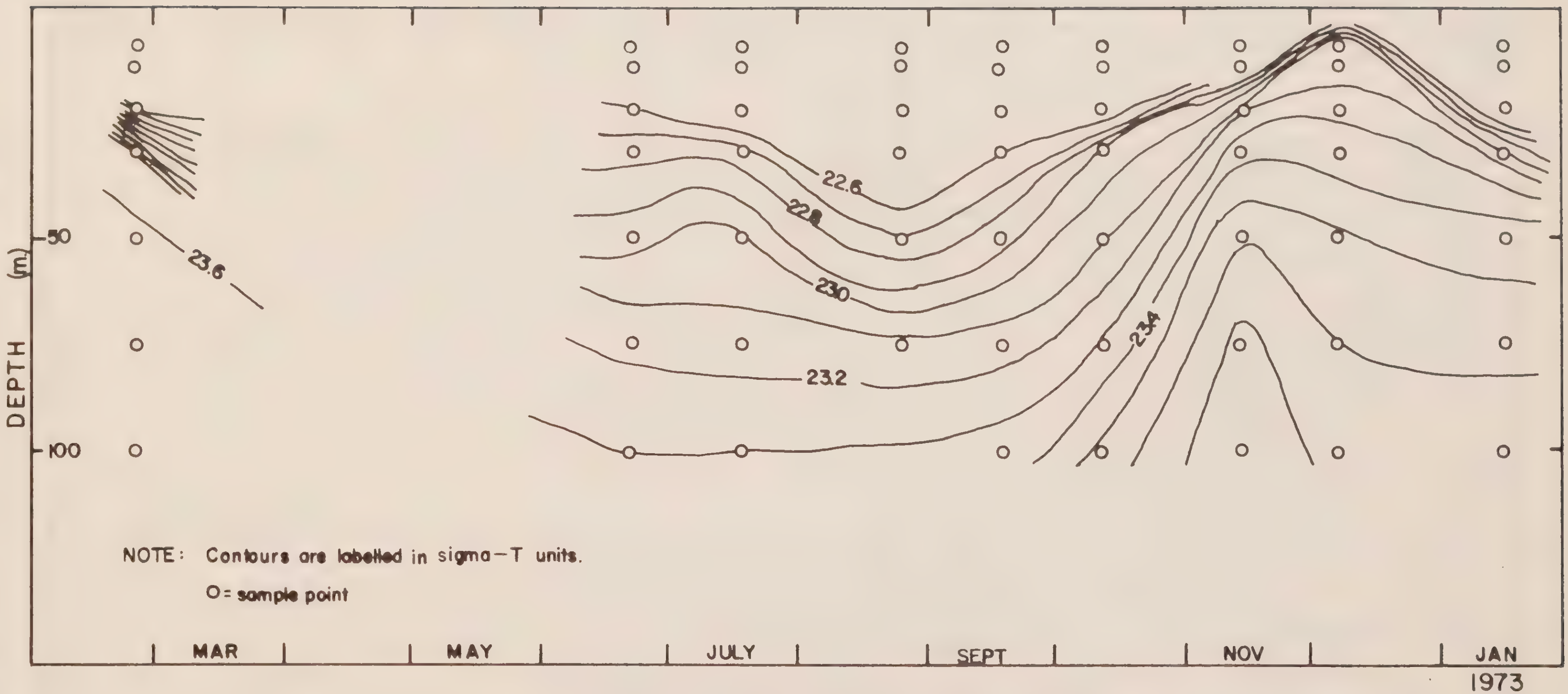

Figure 28. Sigma-t contours near Stn. 4 on a depth-time plot, 1972-73.

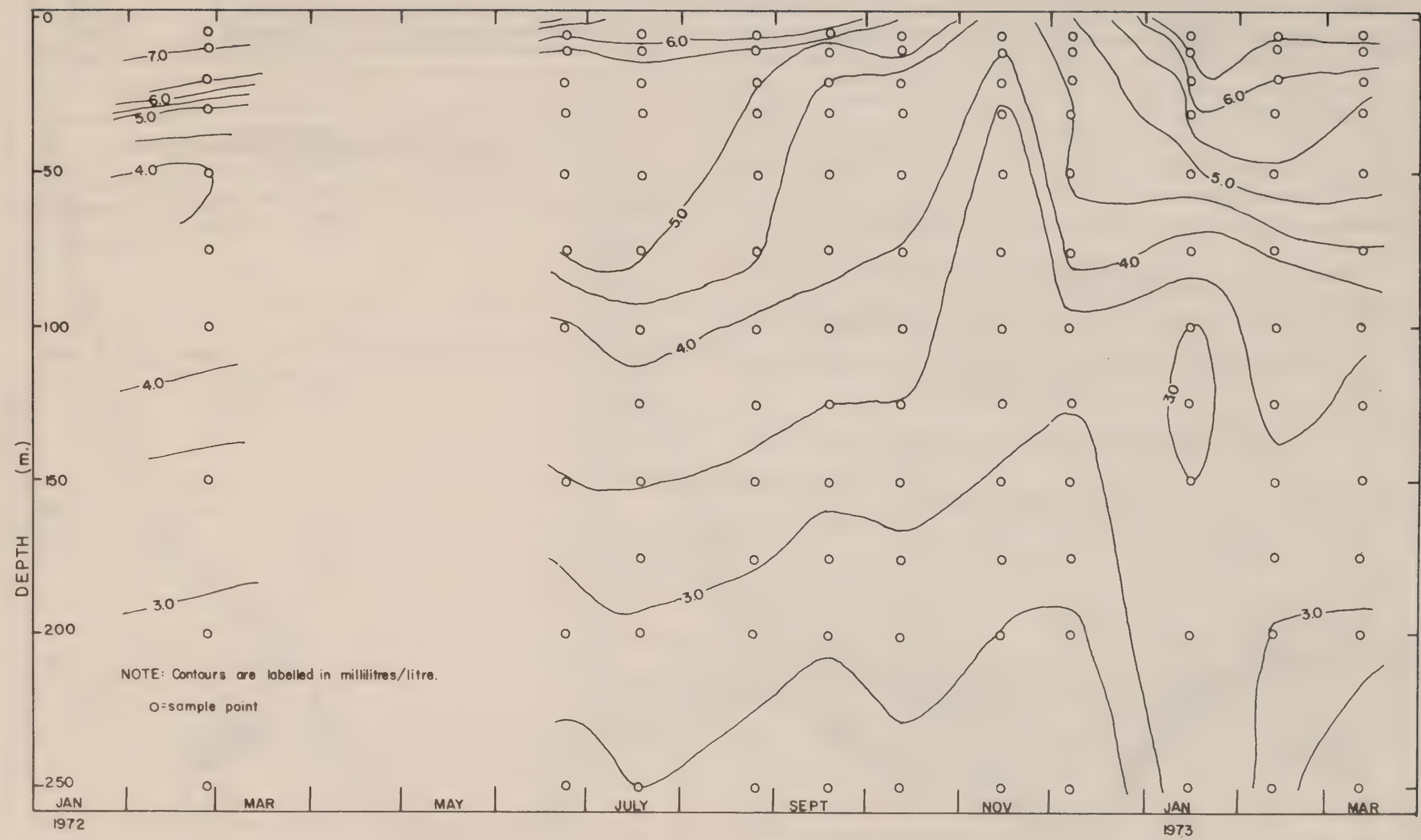

Figure 29. Dissolved oxygen contours near Stn. 5 on a depth-time plot, 1972-73.

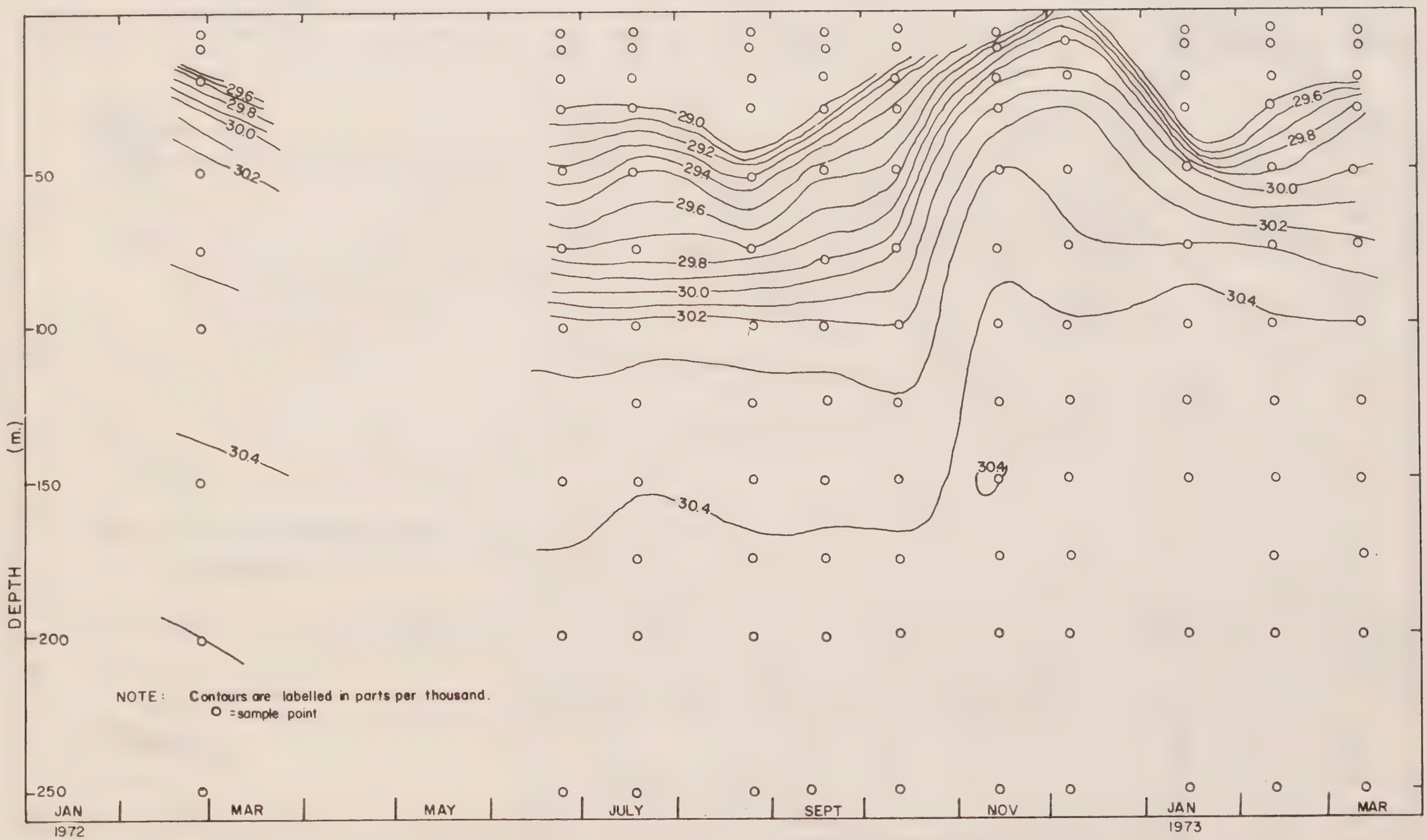

Figure 30. Salinity contours near Stn. 5 on a depth-time plot, 1972-73.

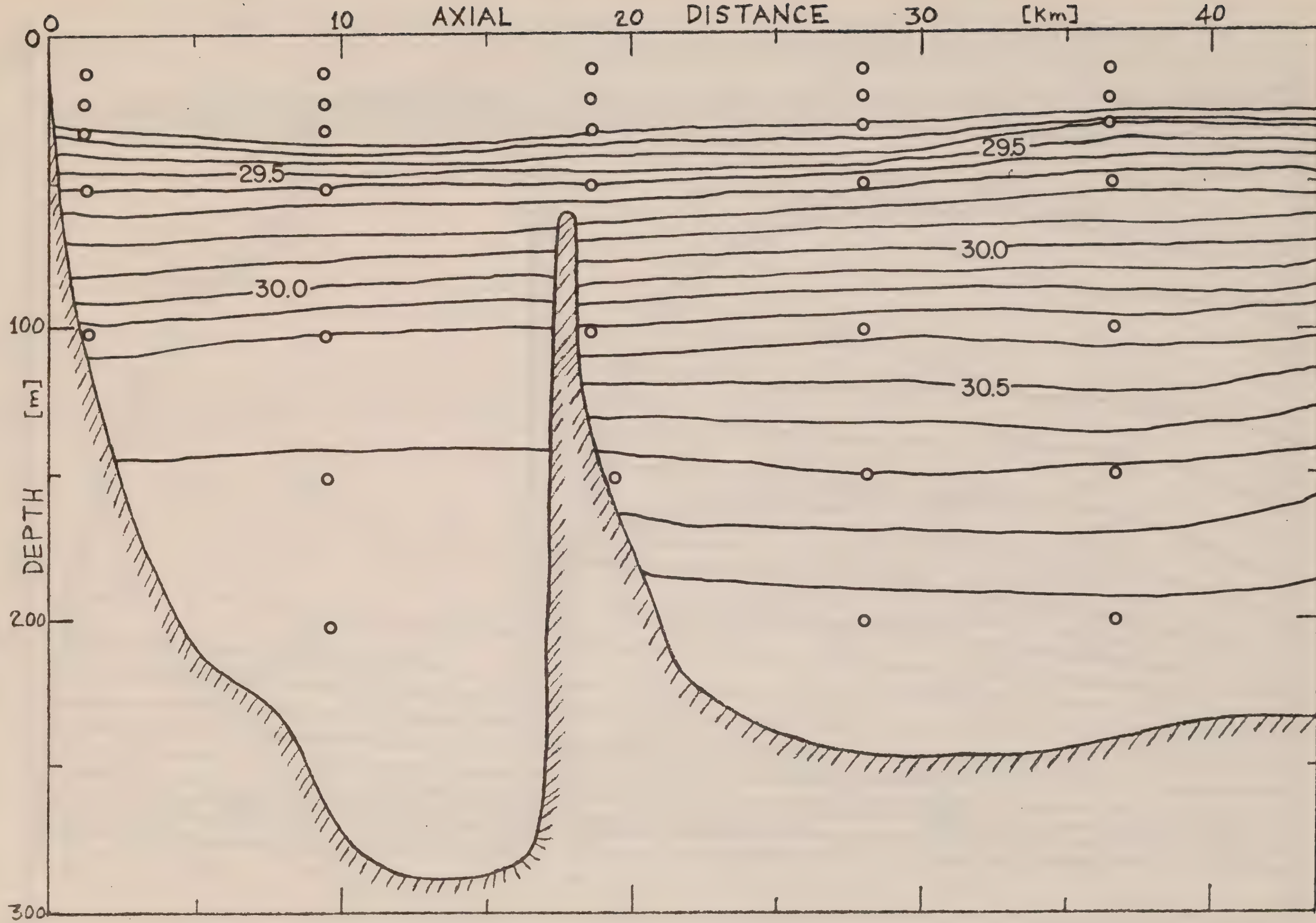

Figure 31. Axial salinity section (from POG data), Oct. 9, 1959.

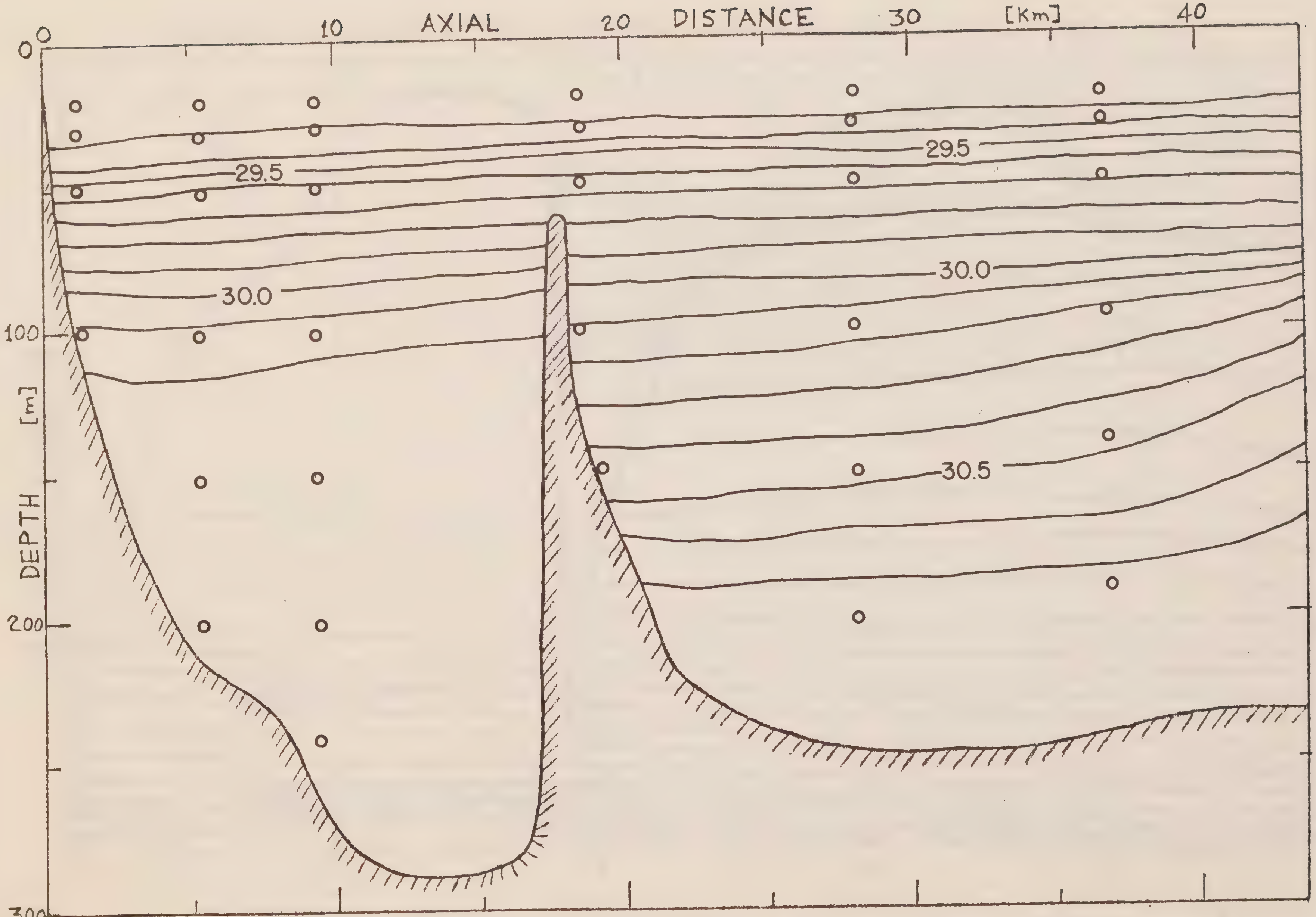

Figure 32. Axial salinity section (from POG data), Sept. 11, 1960.

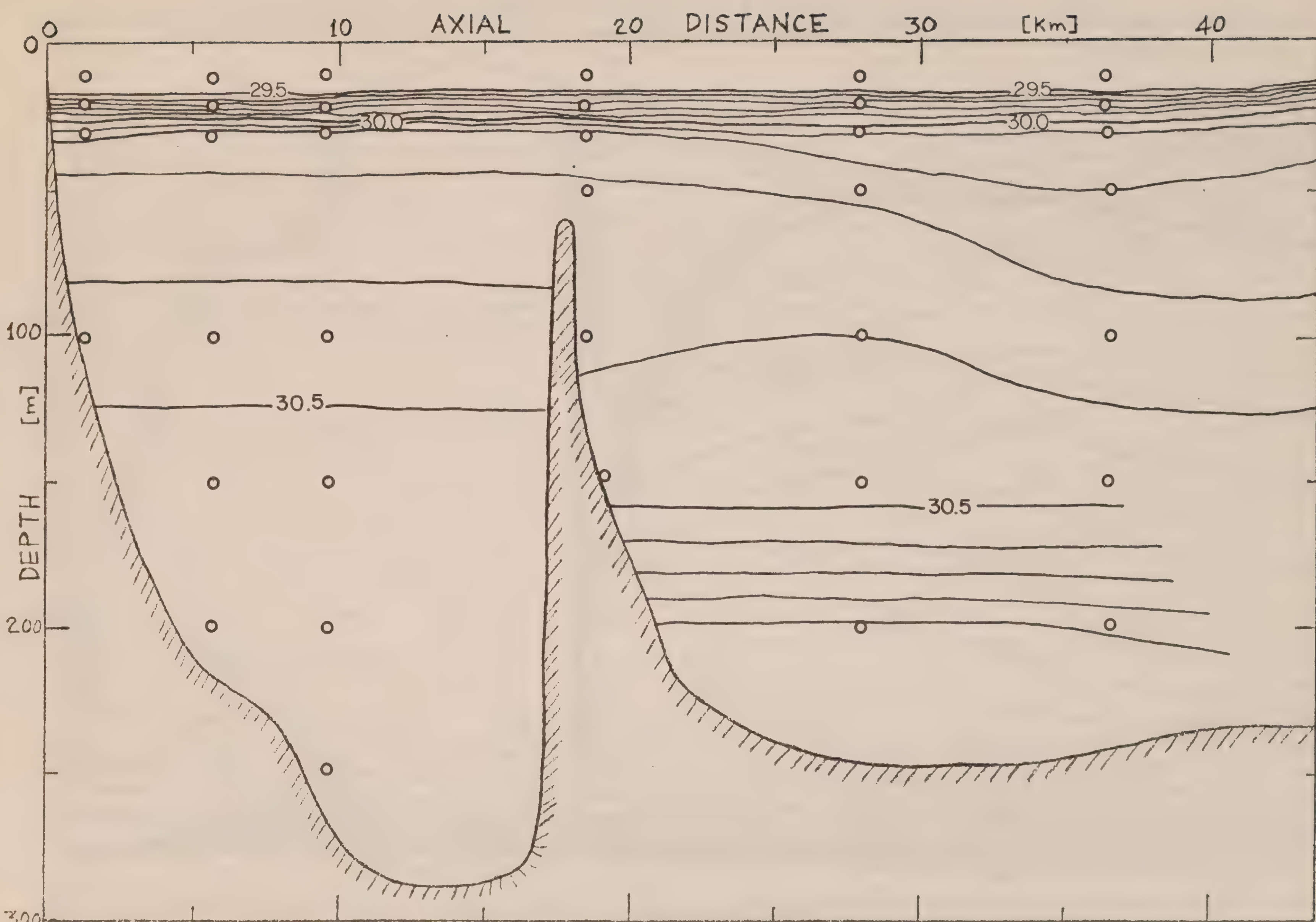

Figure 33. Axial salinity section (from POG data), Feb. 19, 1962.

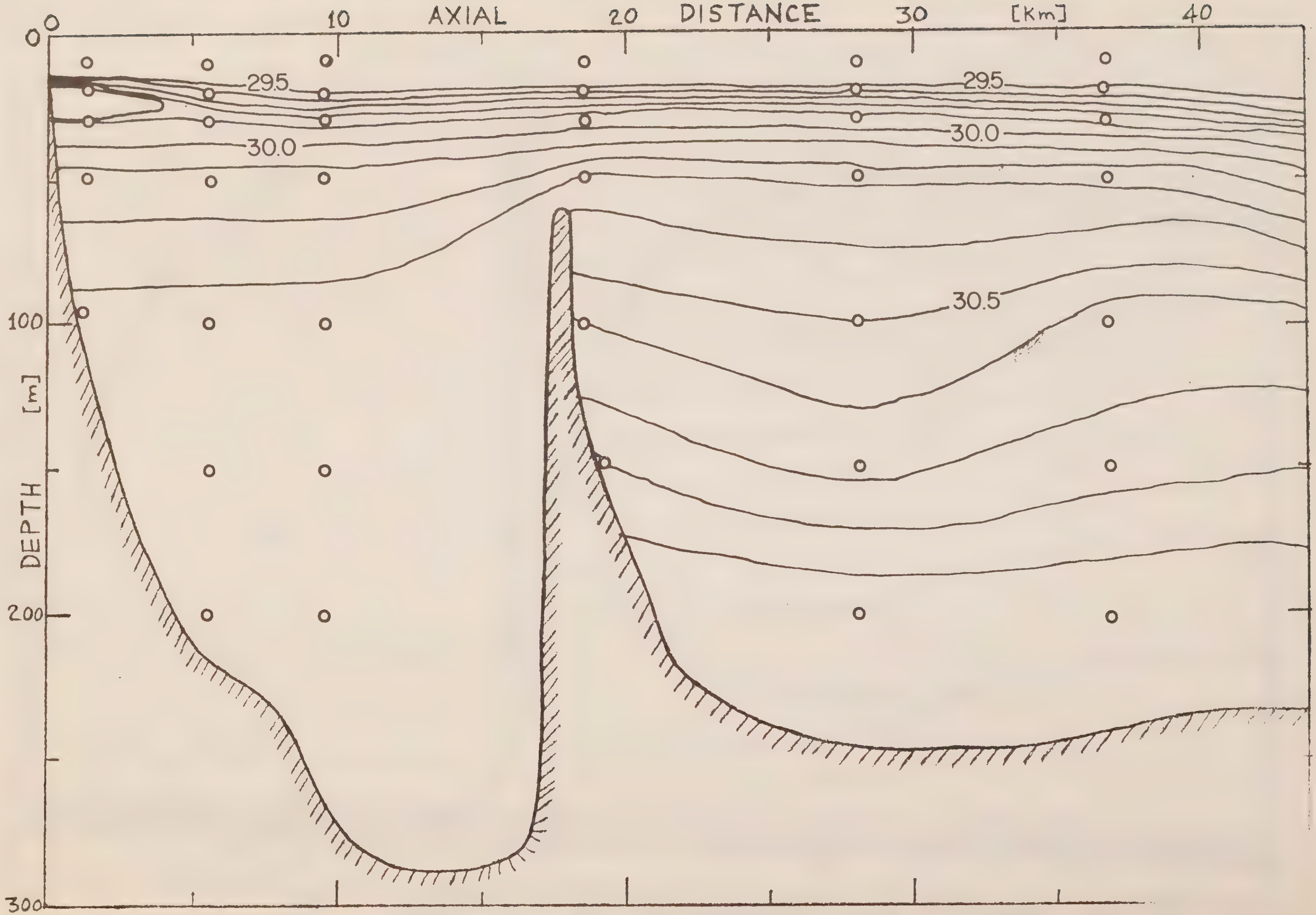

Figure 34. Axial salinity section (from POG data), Sept. 24, 1962.

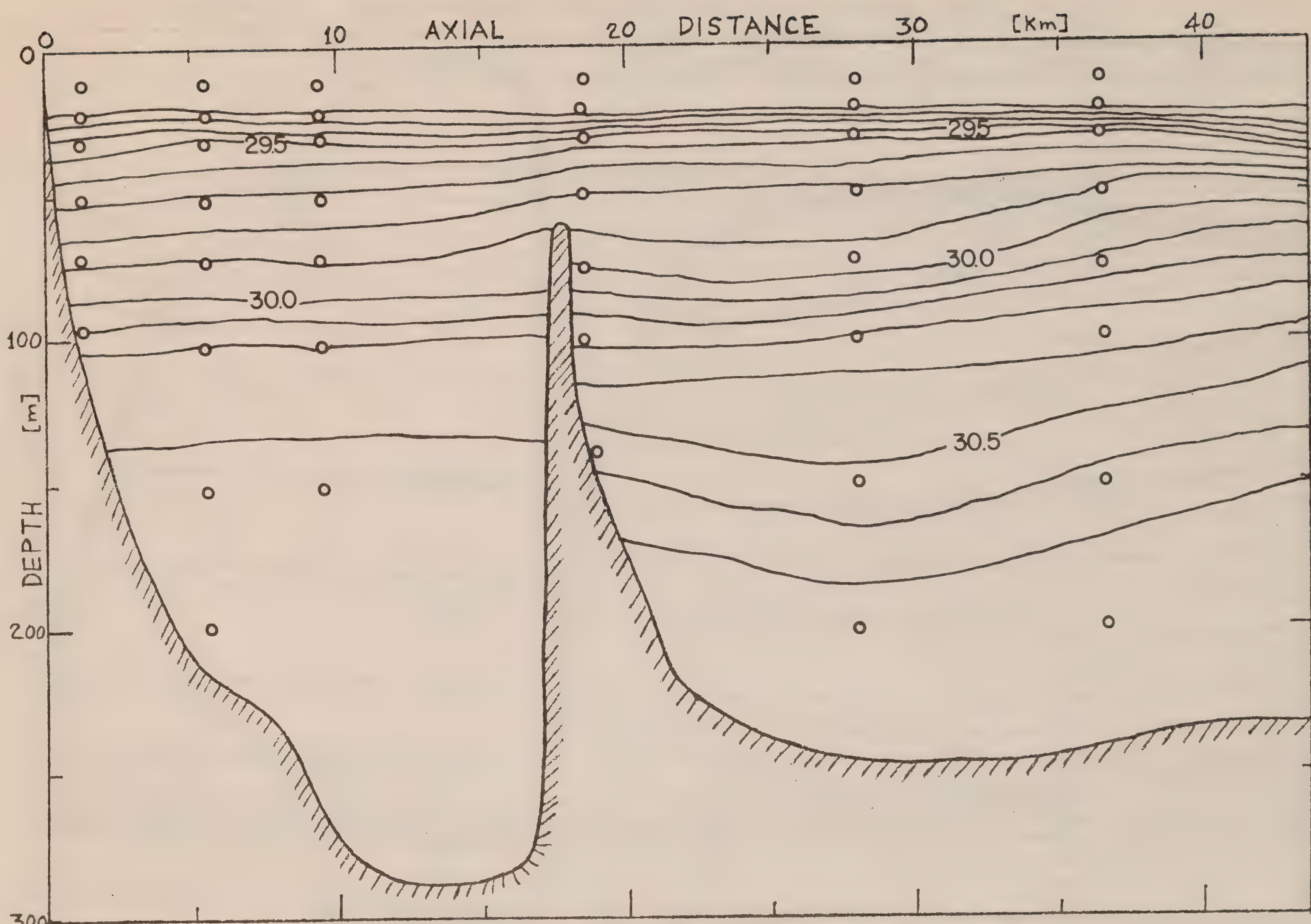

Figure 35. Axial salinity section (from POG data), Aug. 25, 1963.

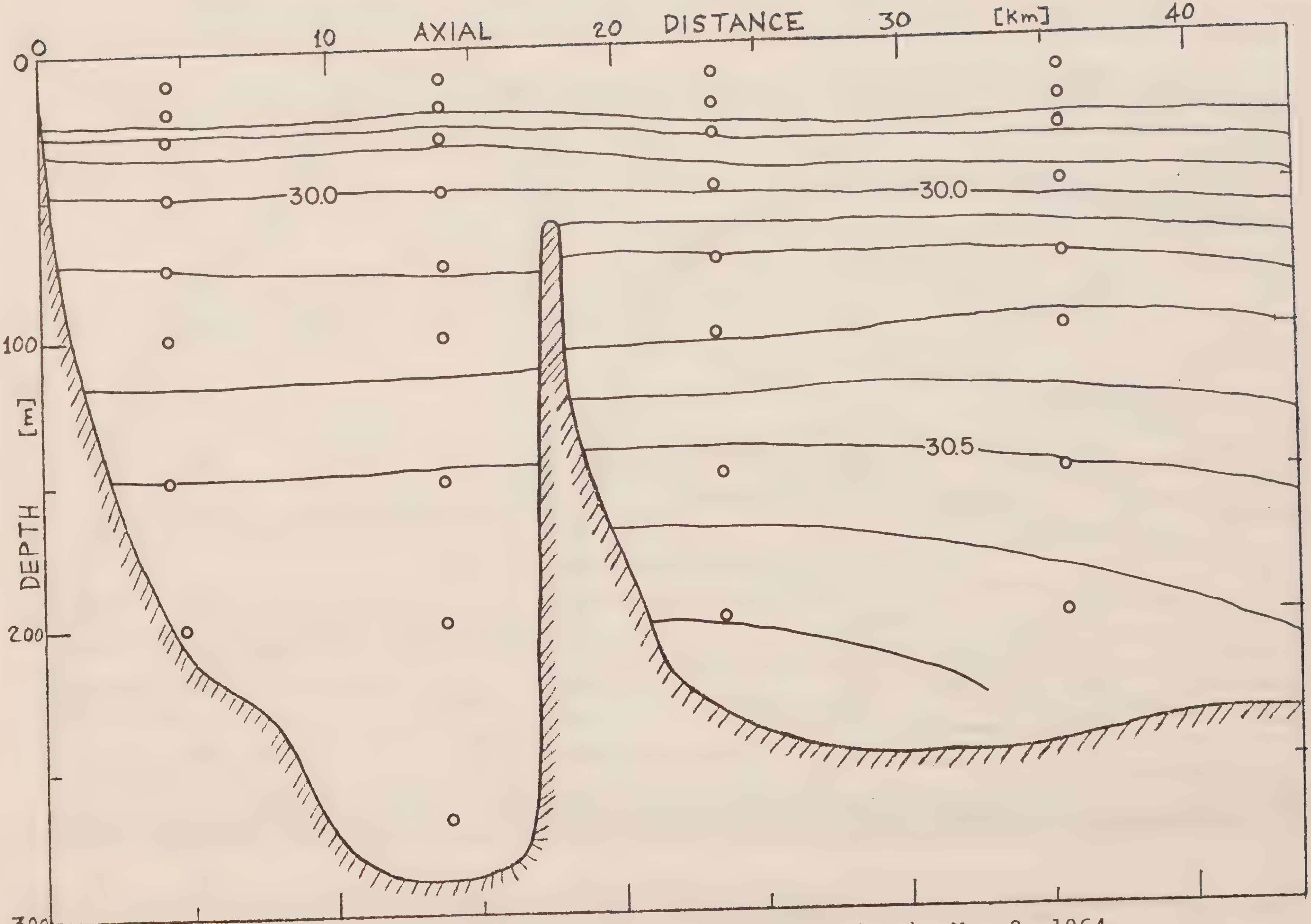

Figure 36. Axial salinity section (from IOUBC data), May 8, 1964.

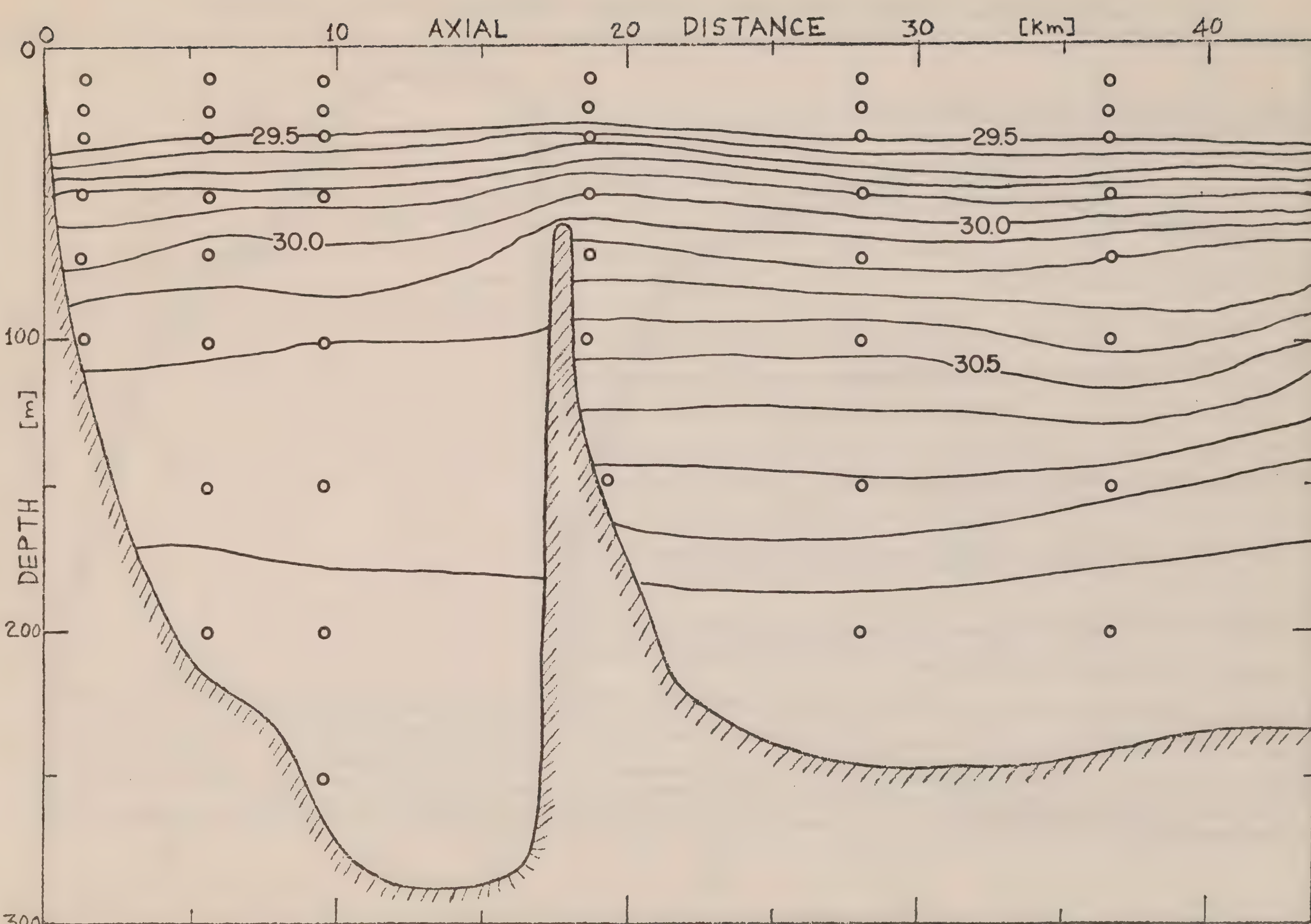

Figure 37. Axial salinity section (from POG data), Sept. 28, 1964.

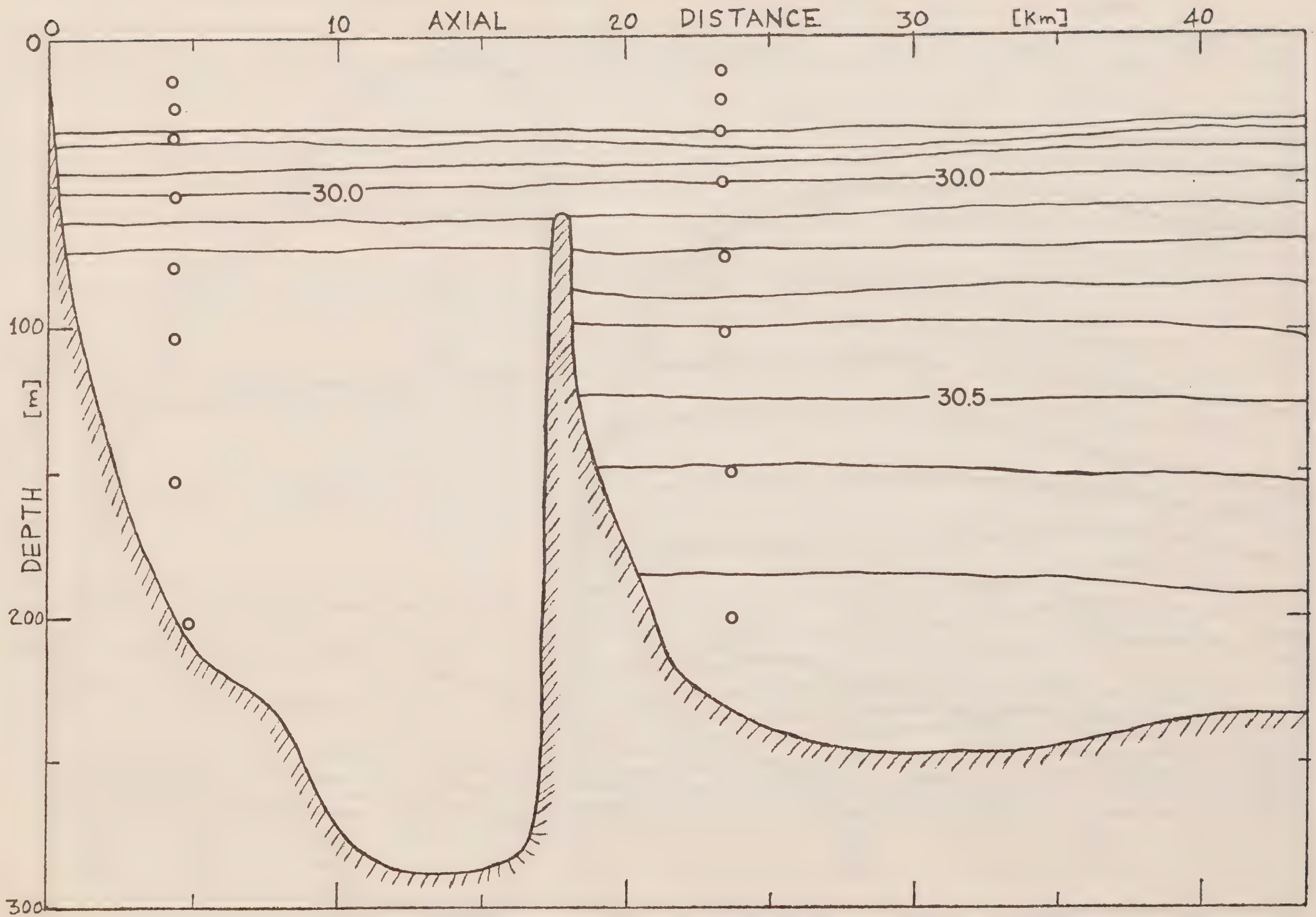

Figure 38. Axial salinity section (from IOUBC data), May 29, 1965.

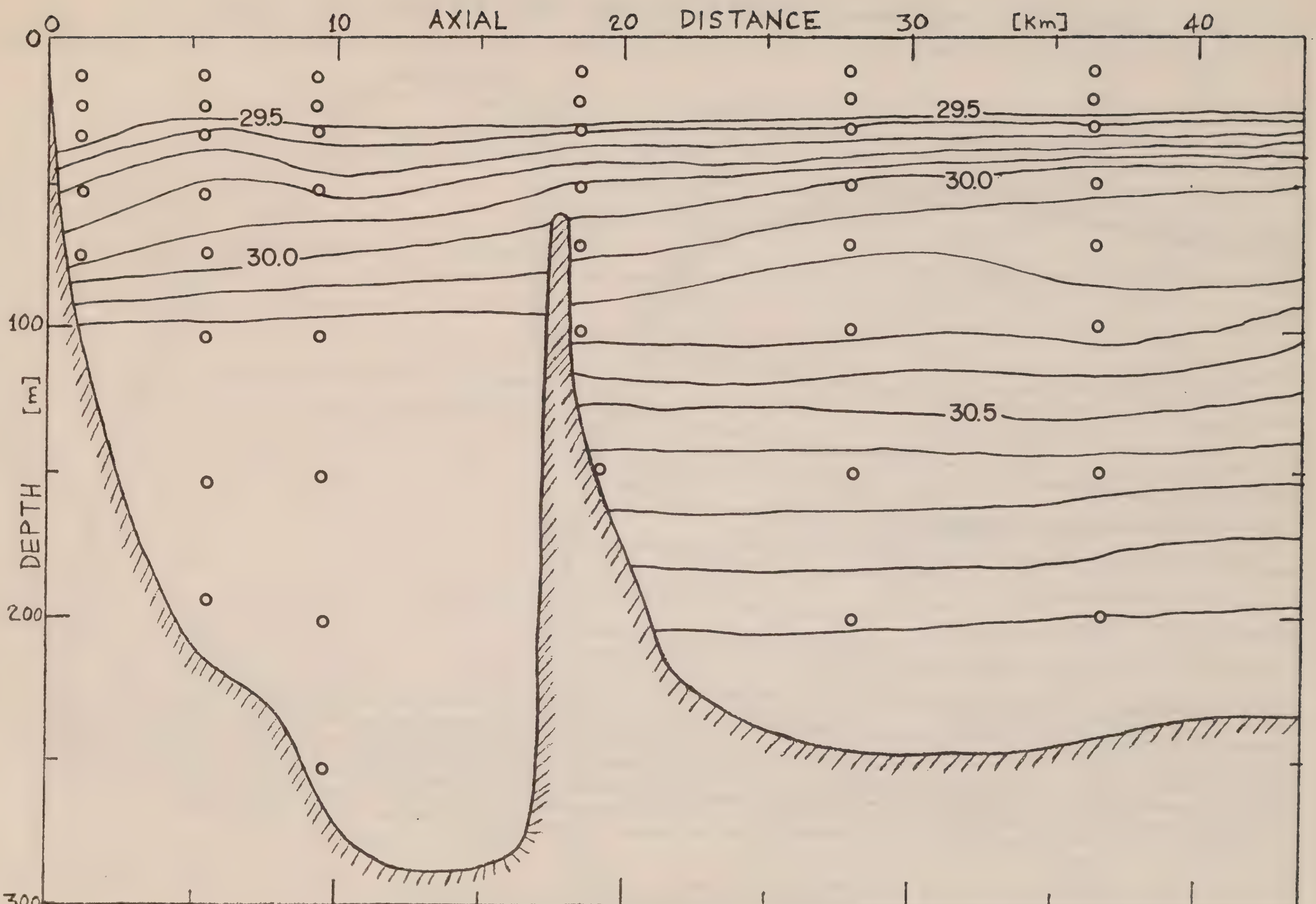

Figure 39. Axial salinity section (from POG data), Aug. 9, 1965.

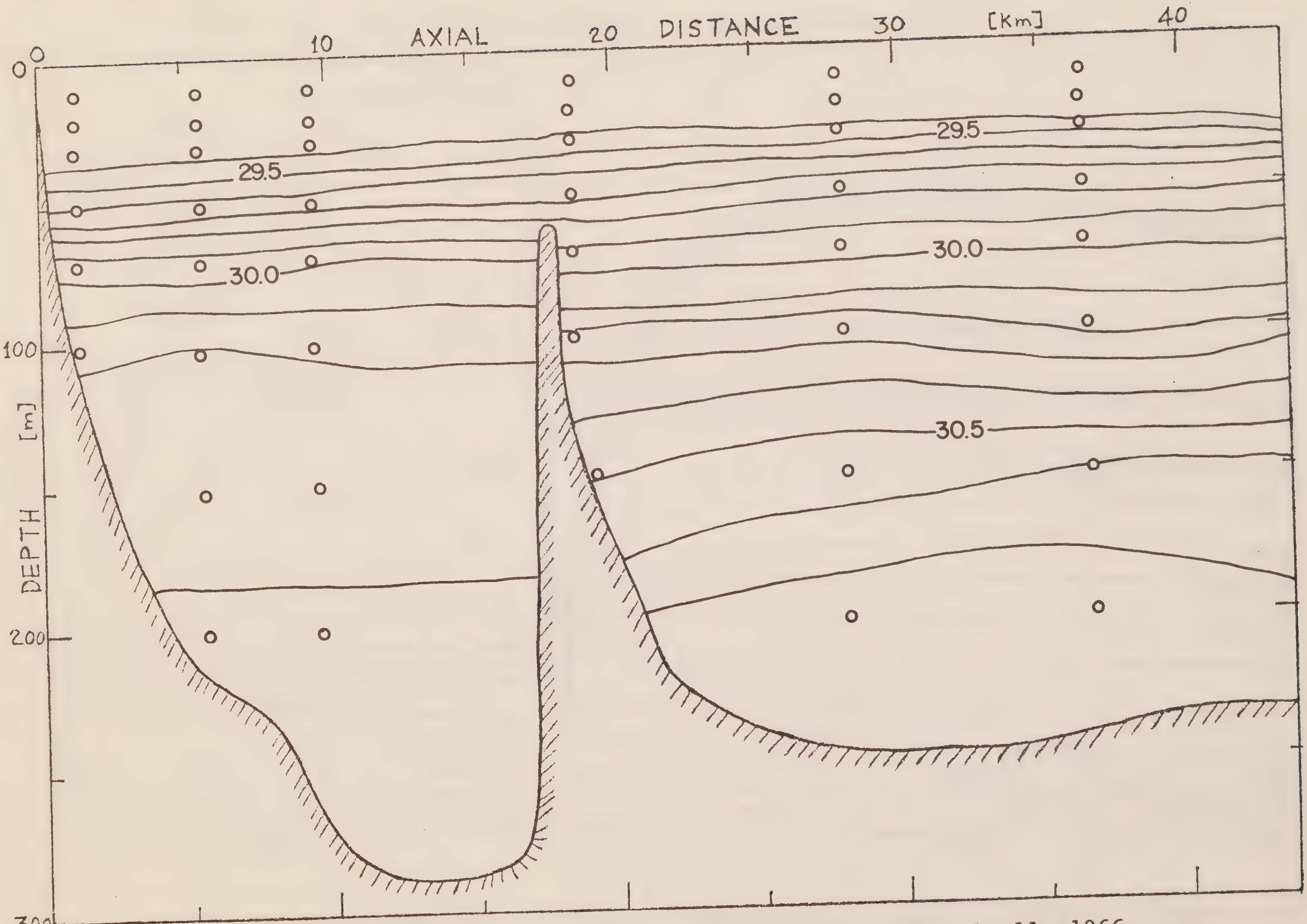

Figure 40. Axial salinity section (from POG data), July 11, 1966.

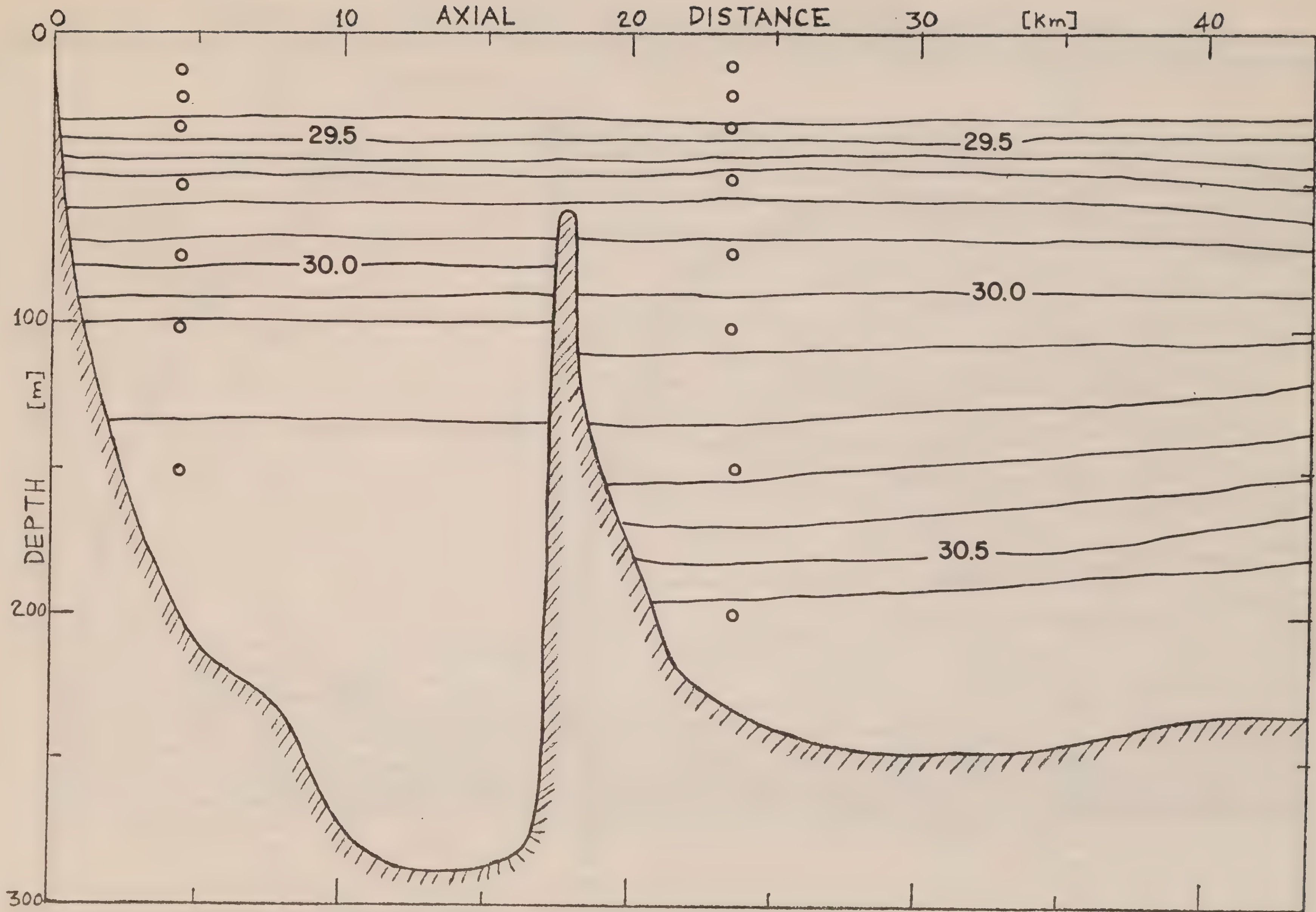

Figure 41. Axial salinity section (from IOUBC data), May 15, 1967.

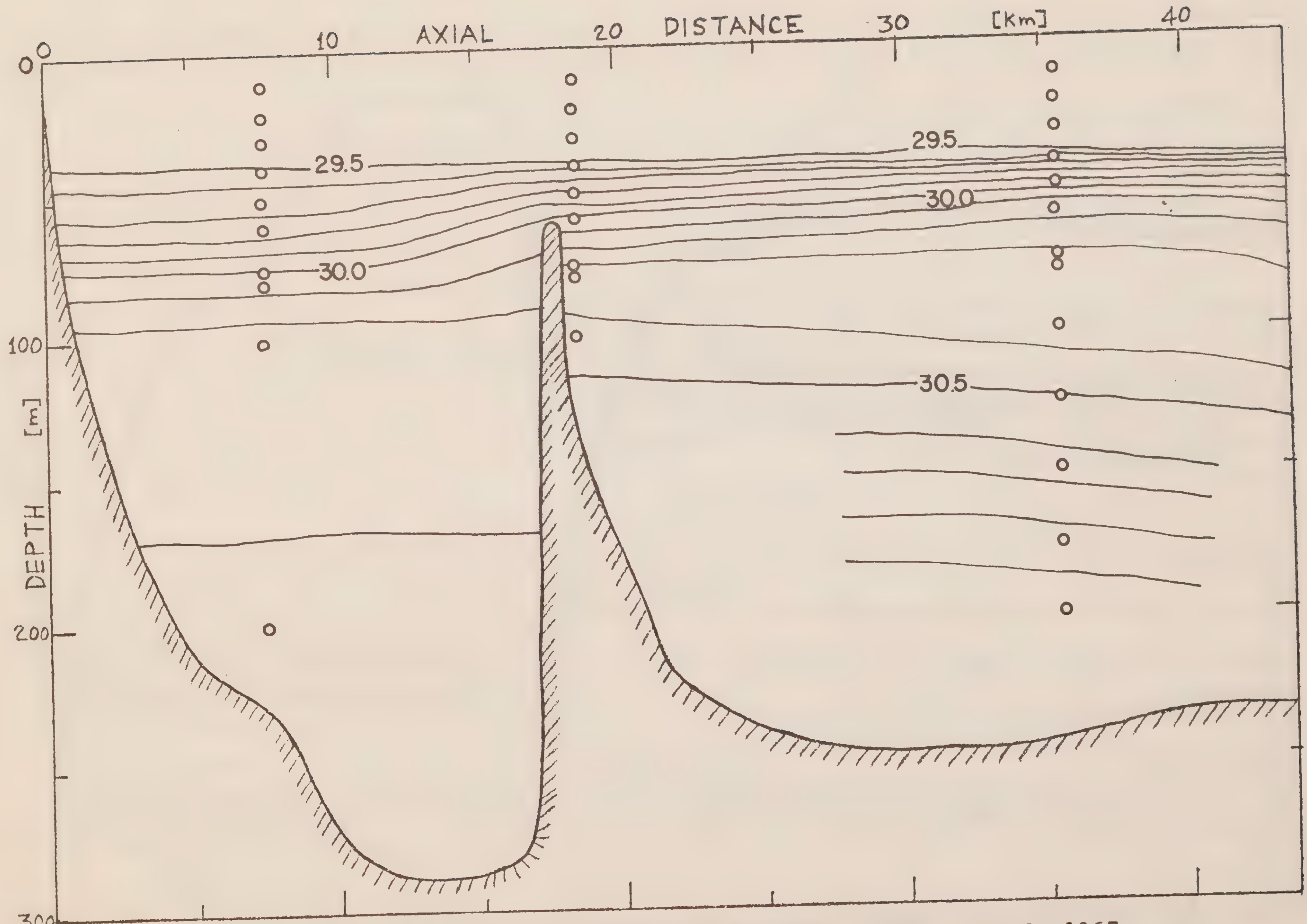

Figure 42. Axial salinity section (from MSB data), Dec. 6, 1967.

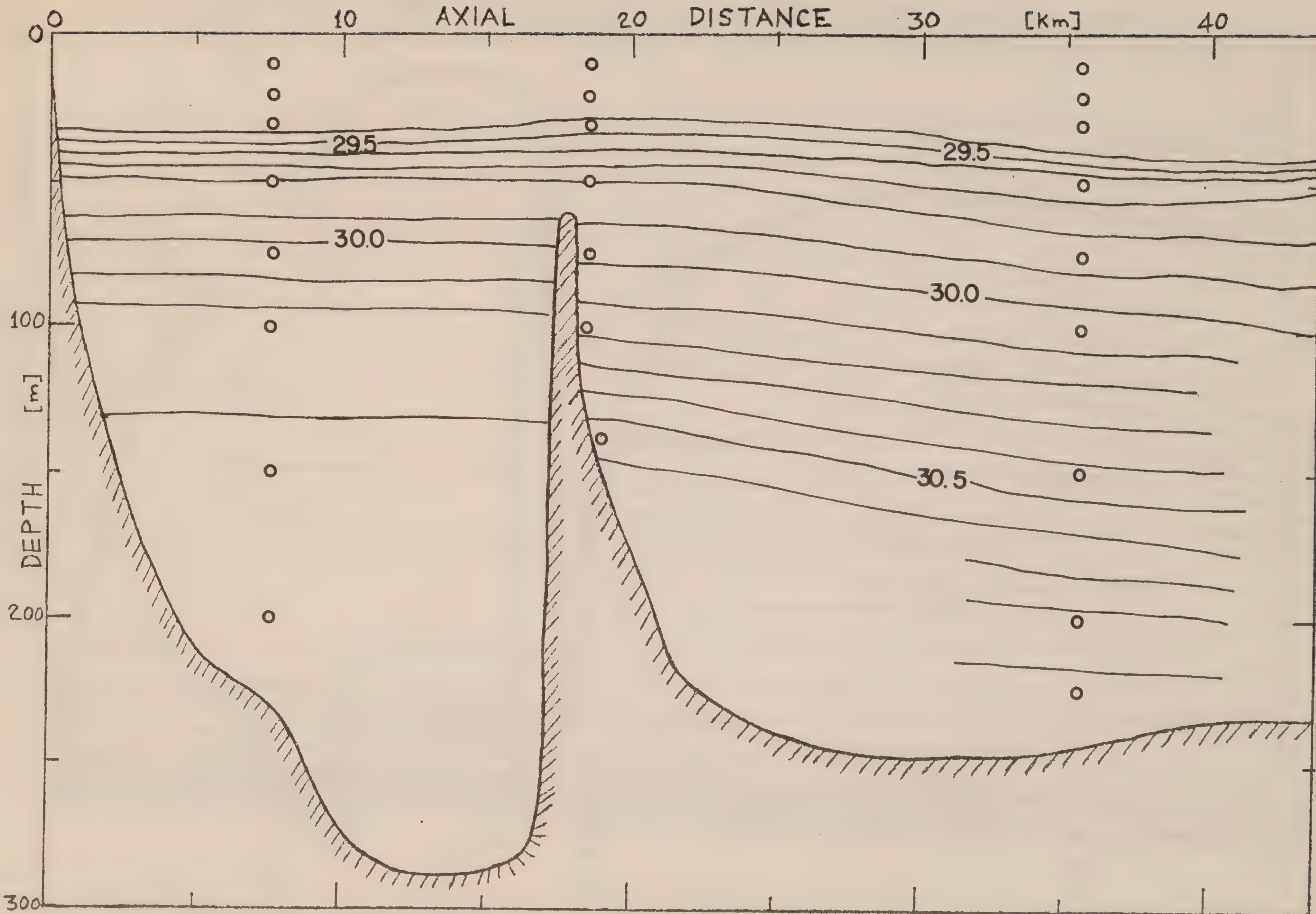

Figure 43. Axial salinity section (from MSB data), Jan. 10, 1968.

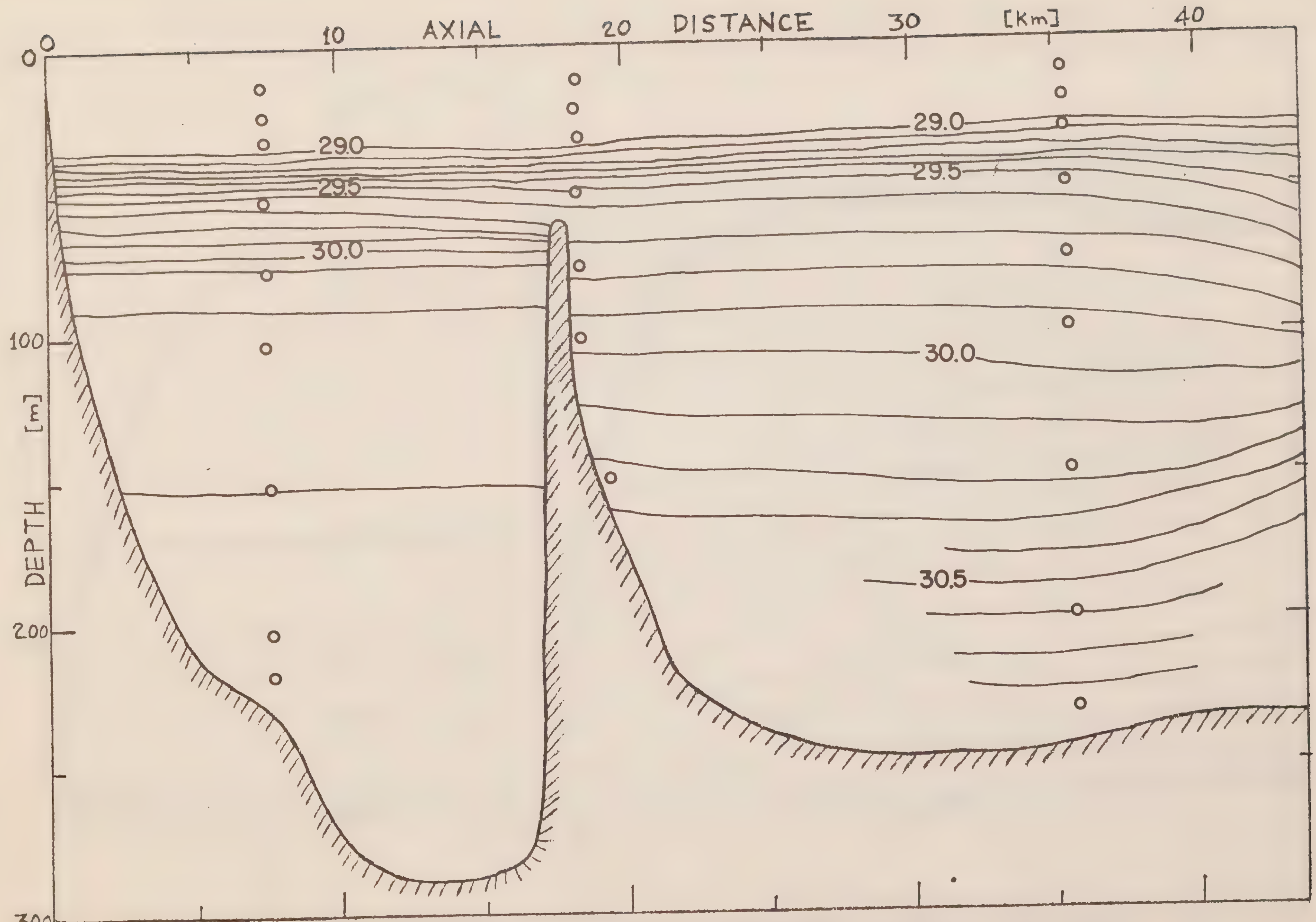

Figure 44. Axial salinity section (from MSB data), Feb. 14, 1968.

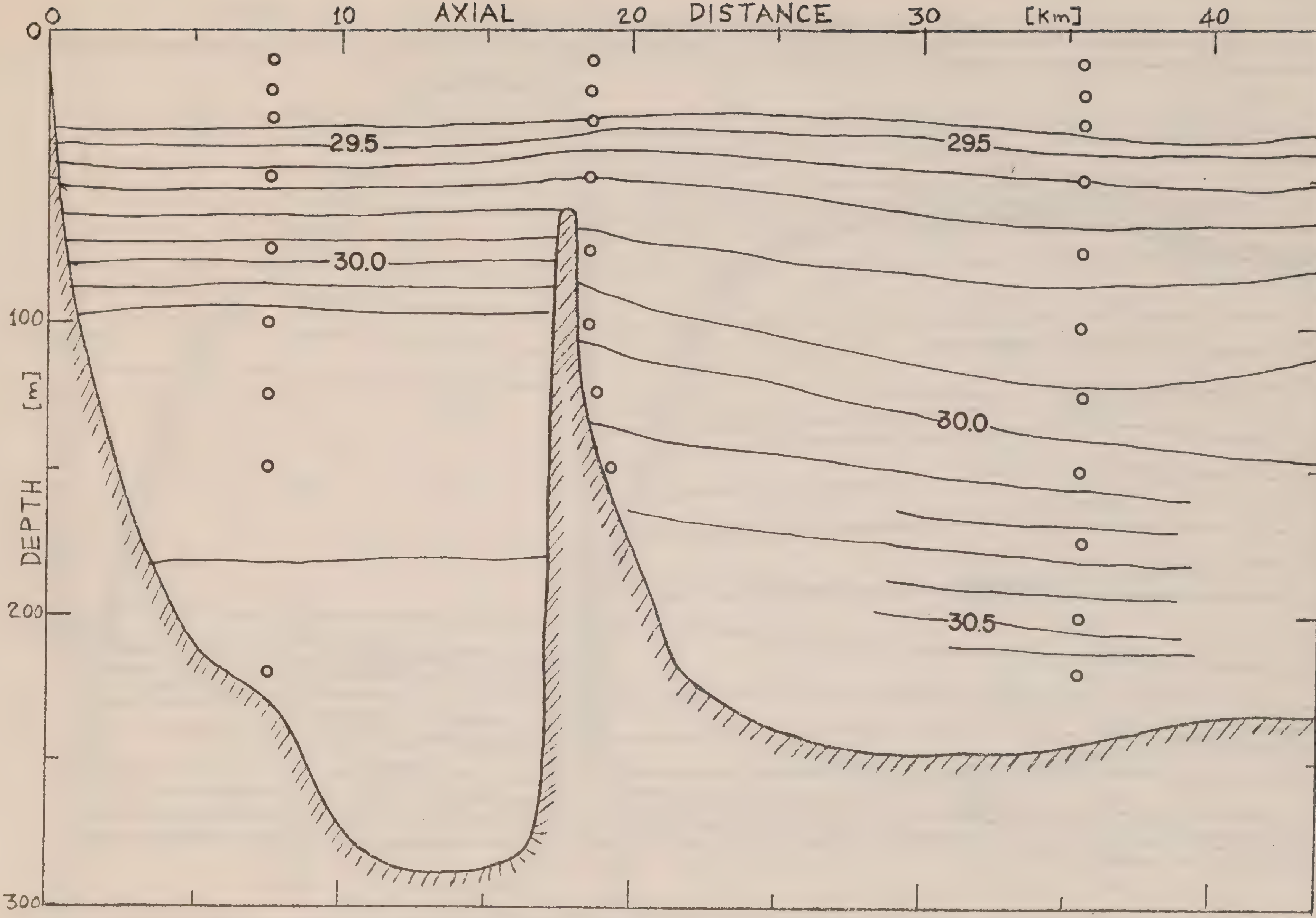

Figure 45. Axial salinity section (from MSB data), Mar. 20, 1968.

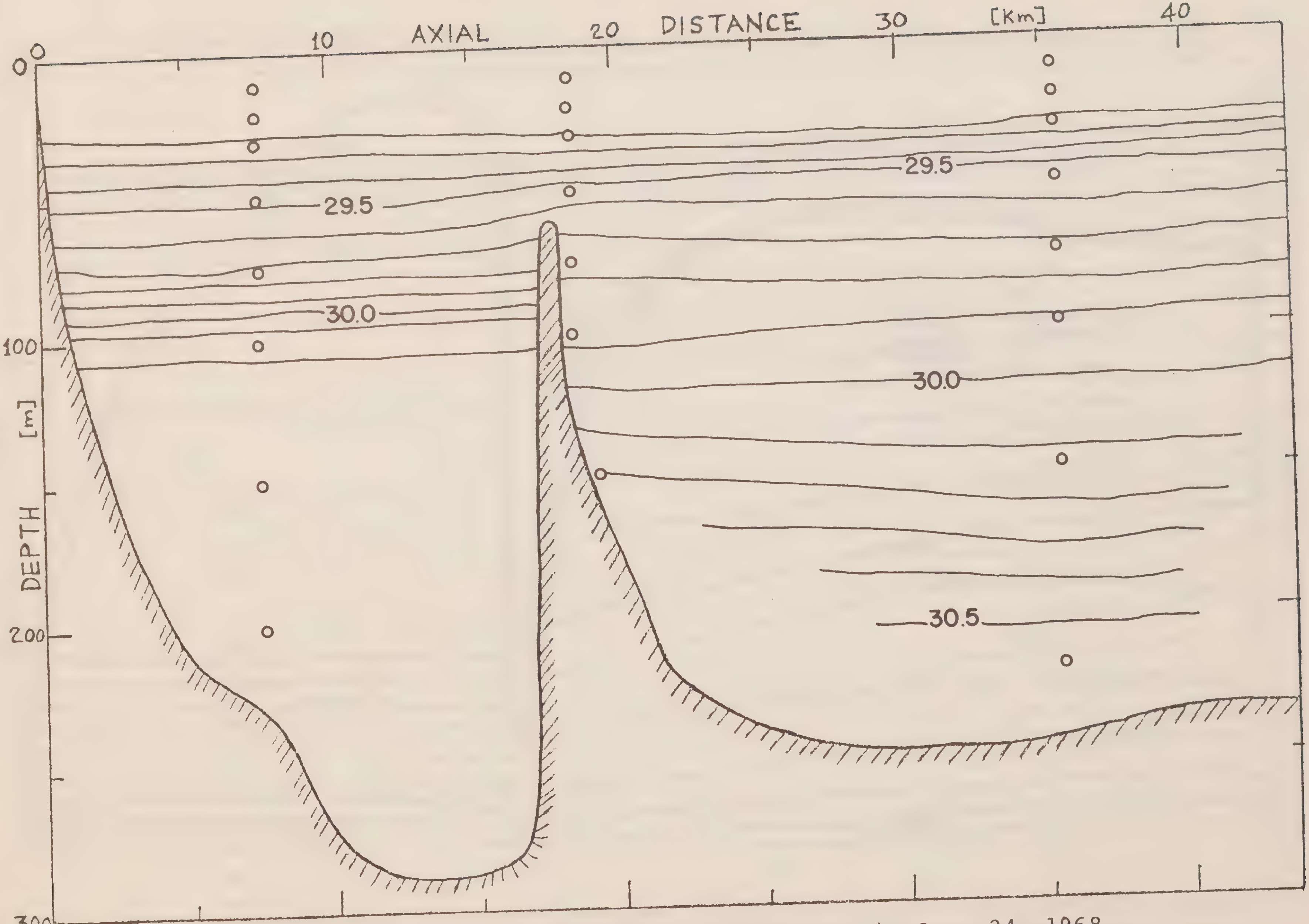

Figure 46. Axial salinity section (from MSB data), Apr. 24, 1968.

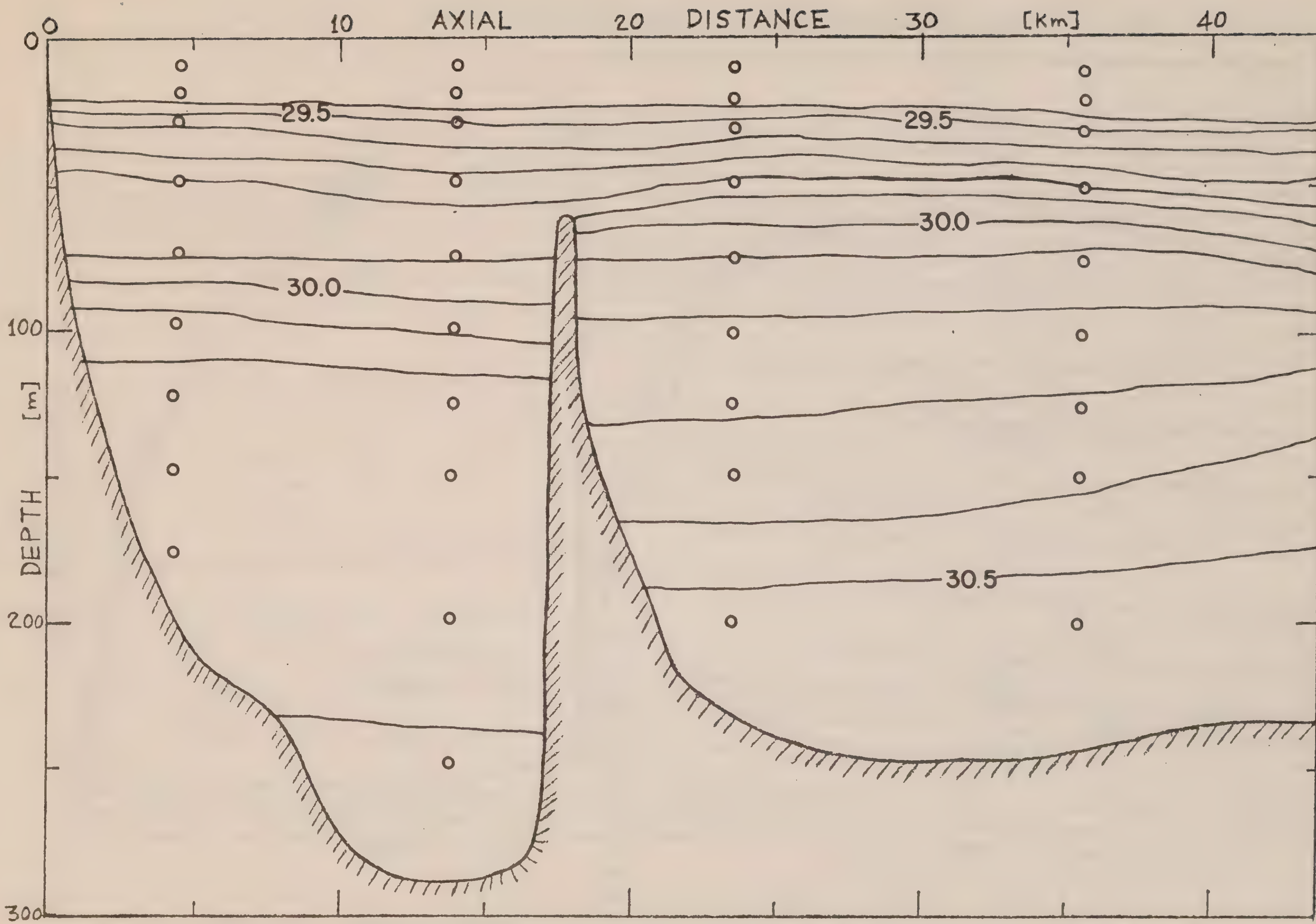

Figure 47. Axial salinity section (from IOUBC data), May 23, 1968.

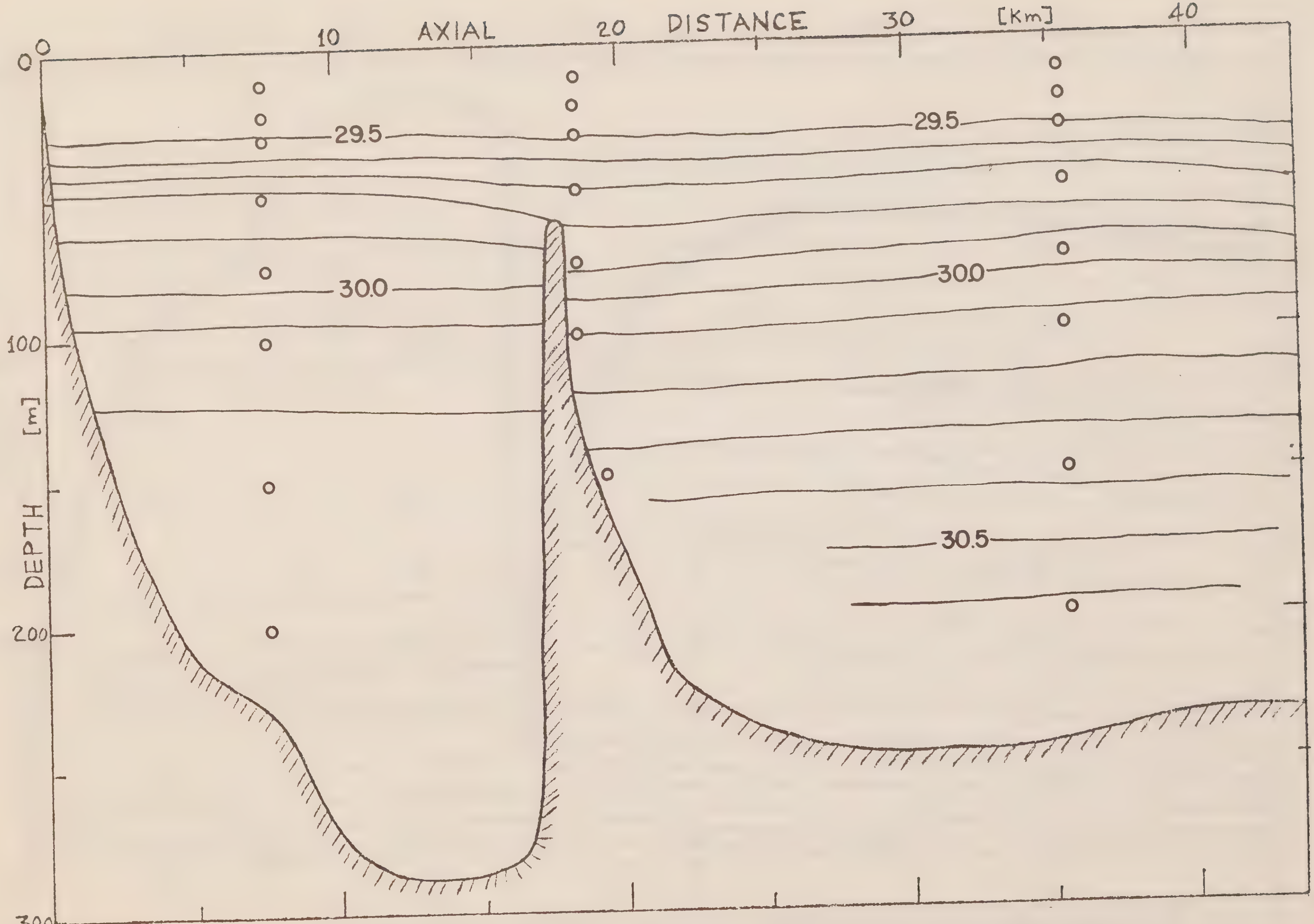

Figure 48. Axial salinity section (from MSB data), May 29, 1968.

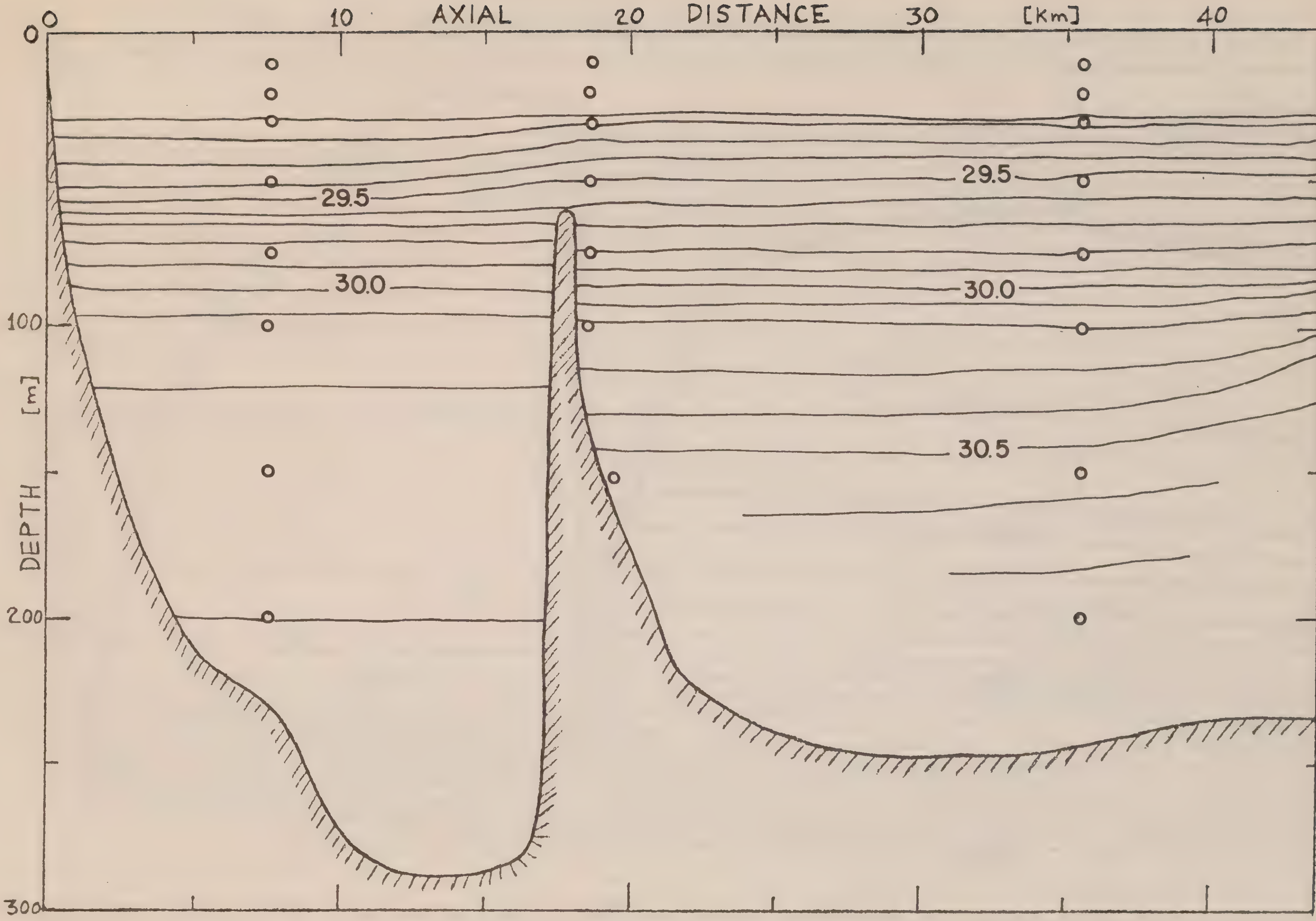

Figure 49. Axial salinity section (from MSB data), July 4, 1968.

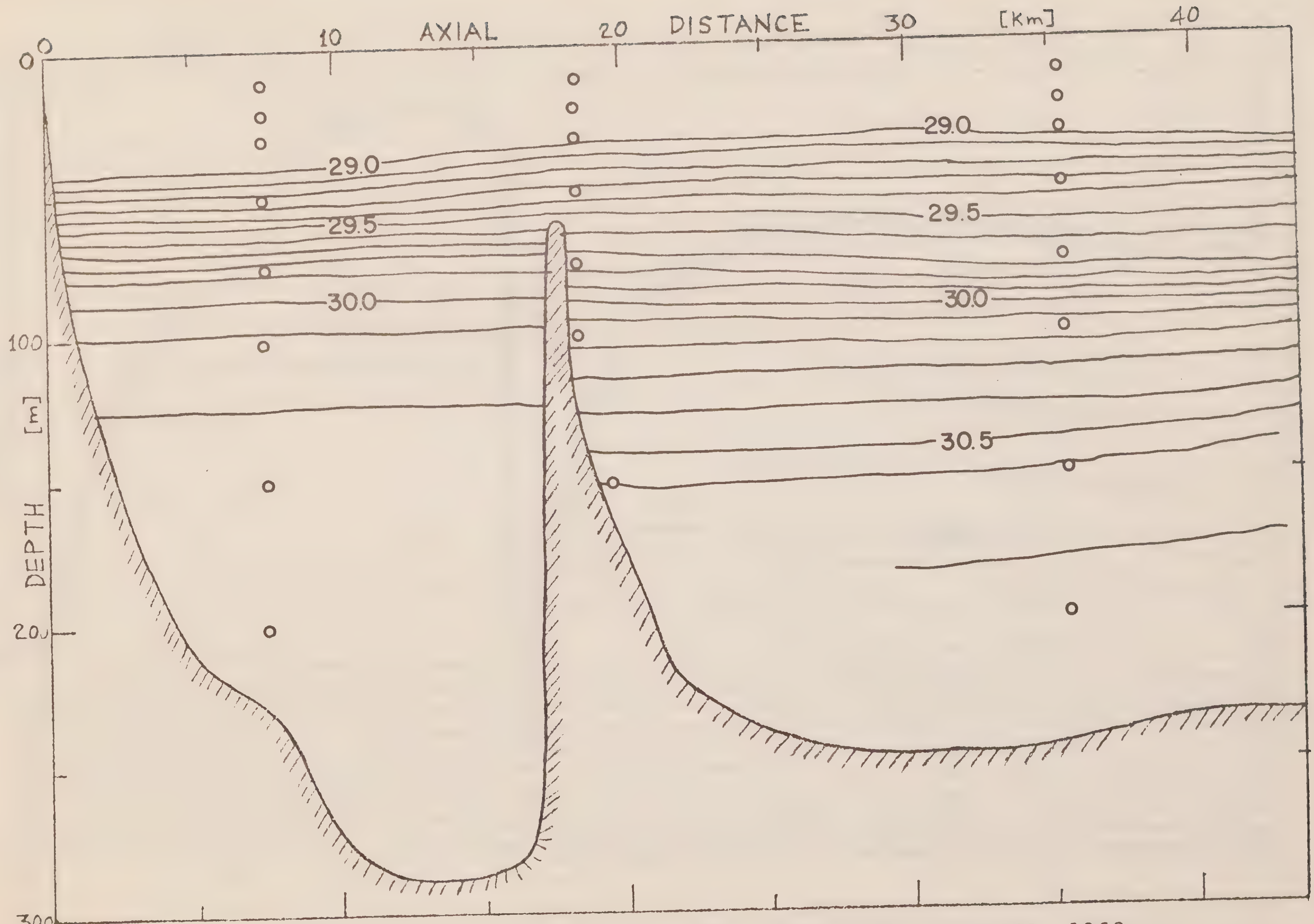

Figure 50. Axial salinity section (from MSB data), July 31, 1968.

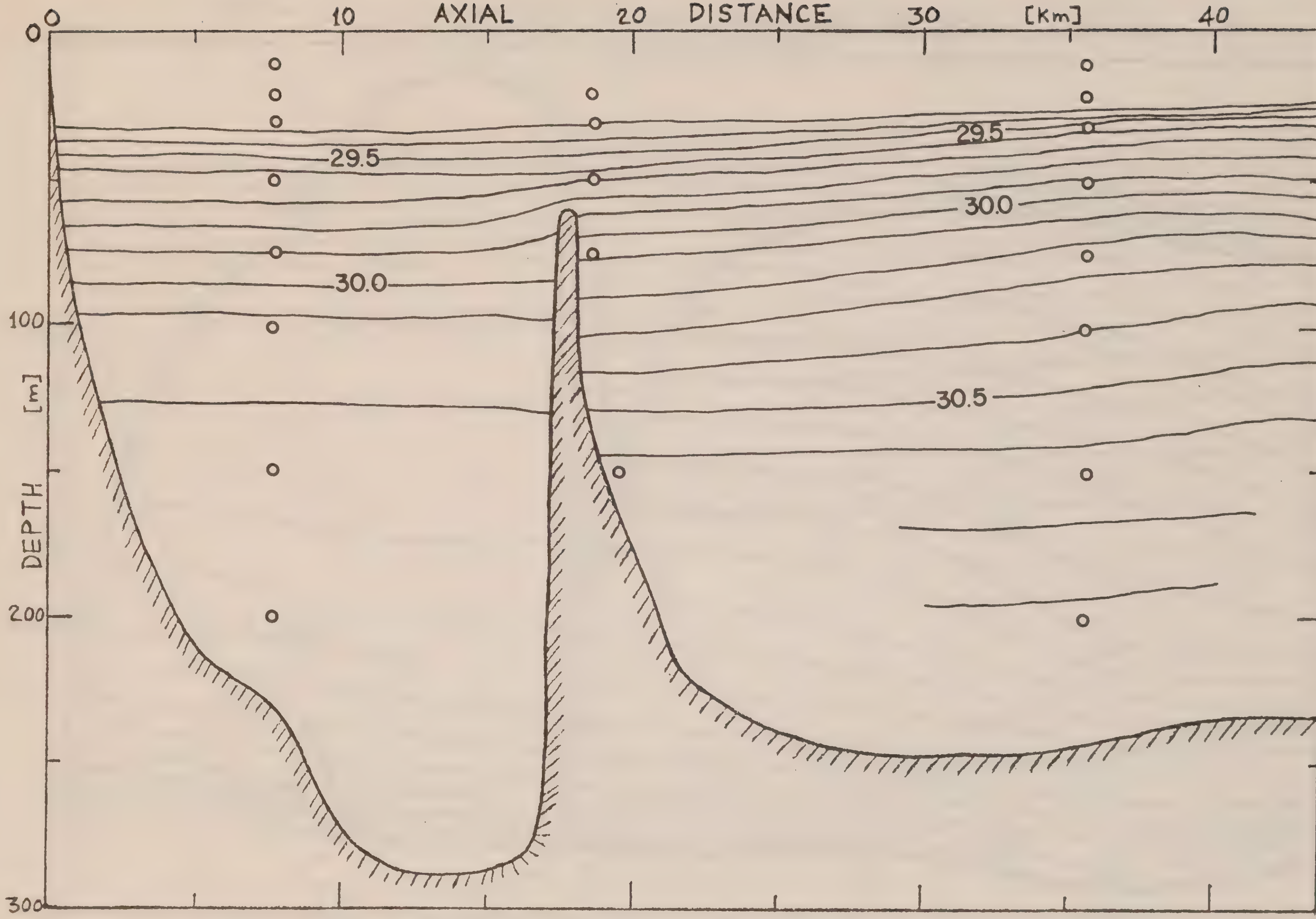

Figure 51. Axial salinity section (from MSB data), Aug. 28, 1968.

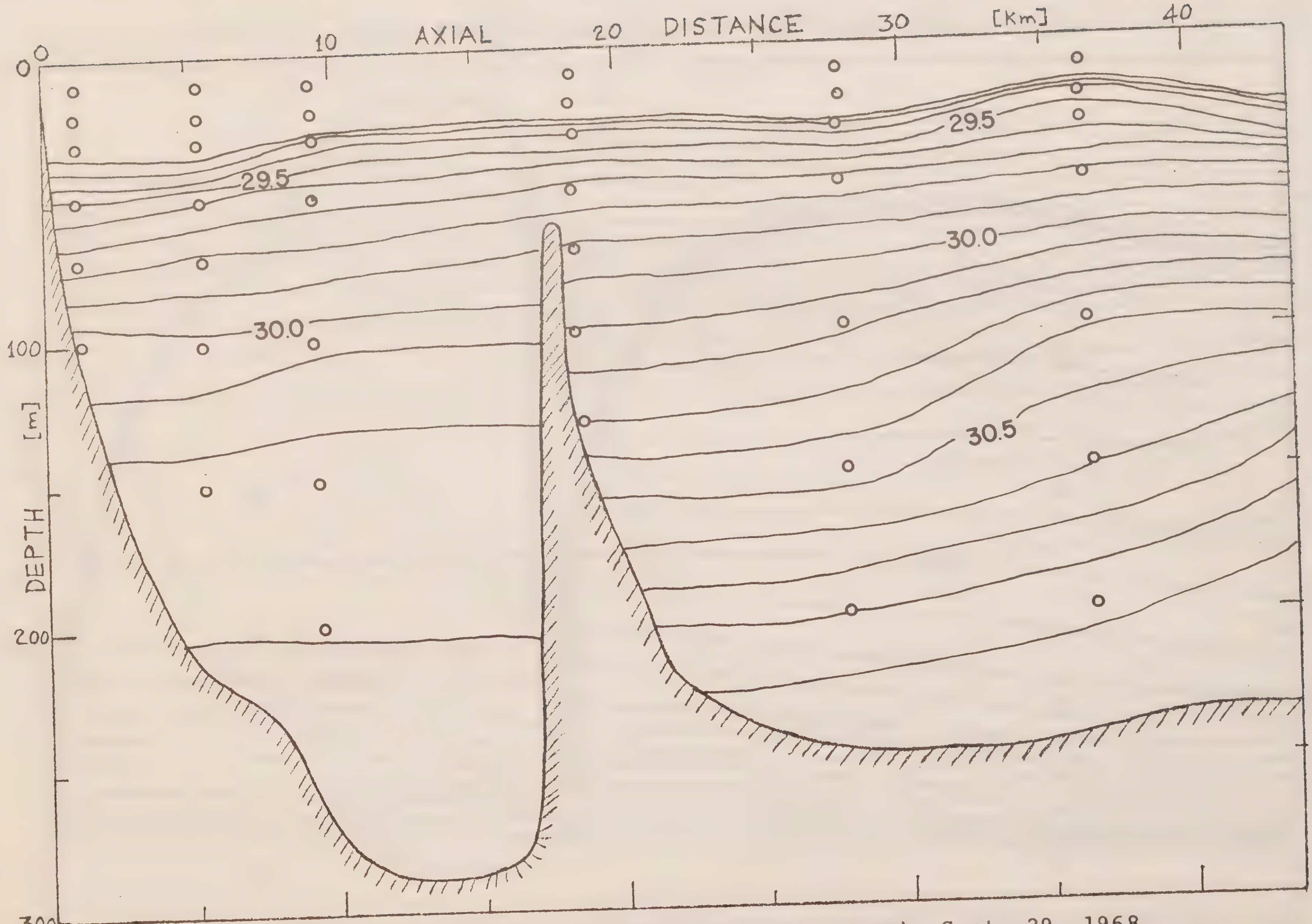

Figure 52. Axial salinity section (from POG data), Sept. 29, 1968.

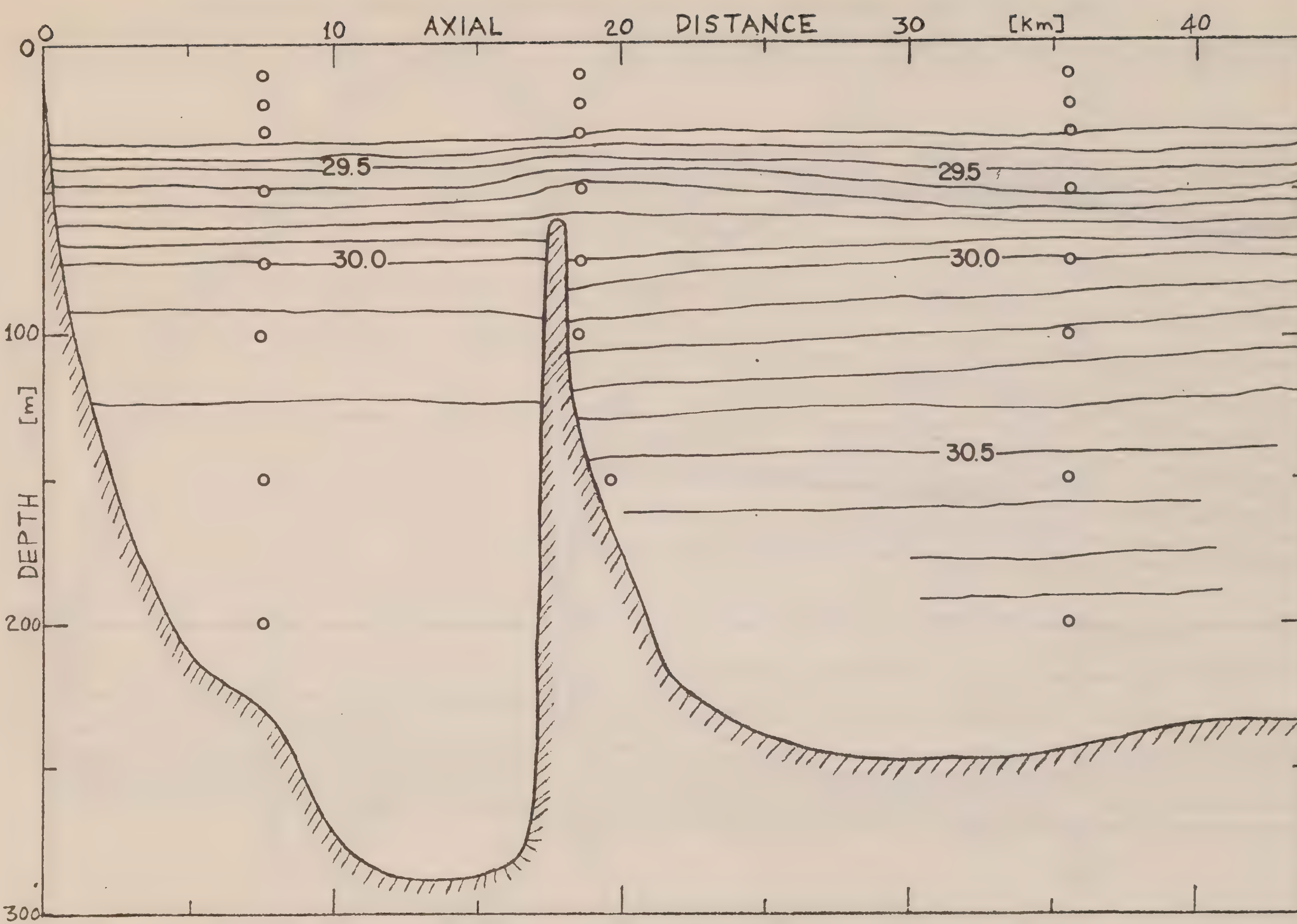

Figure 53. Axial salinity section (from MSB data), Oct. 3, 1968.

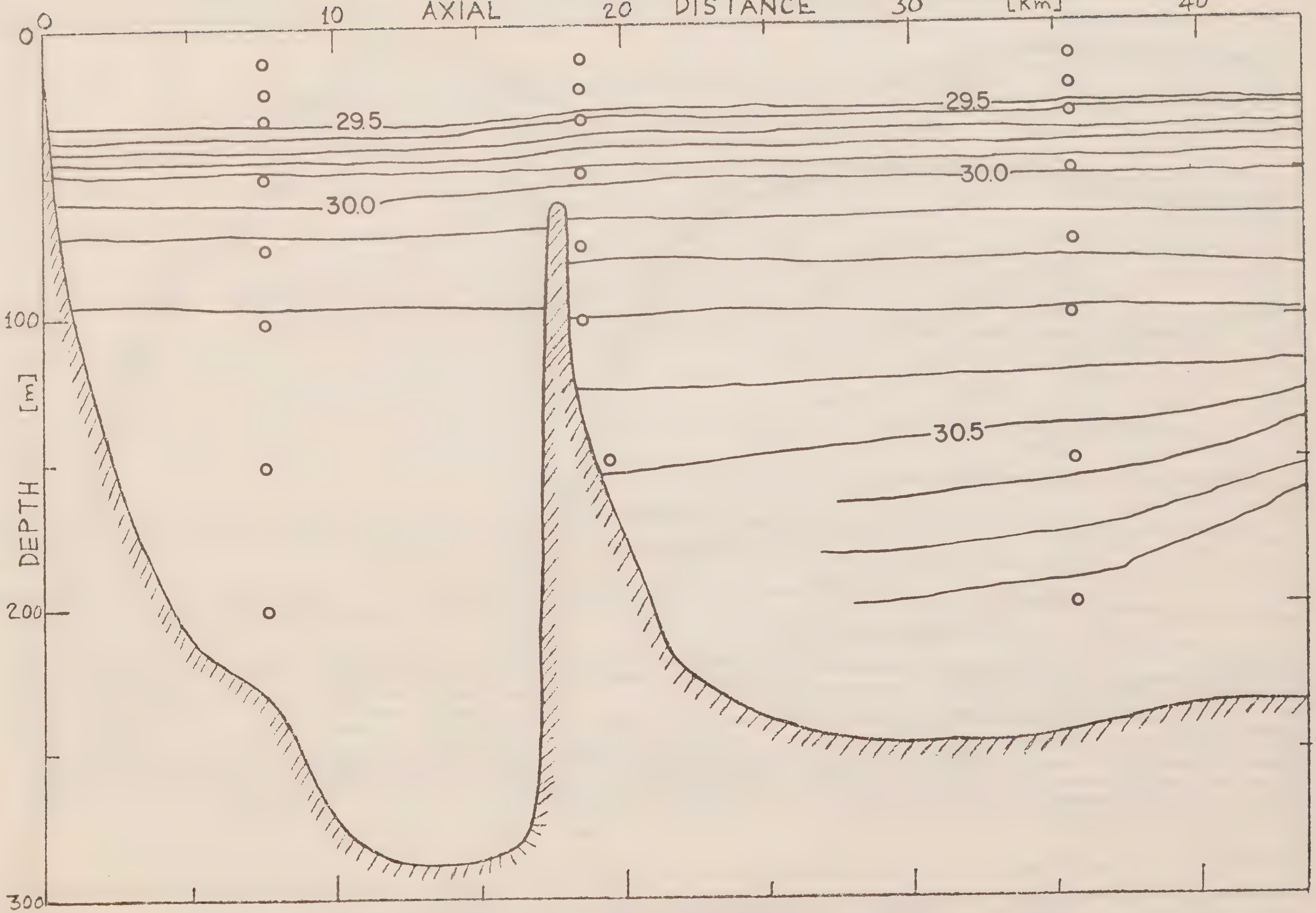

Figure 54. Axial salinity section (from MSB data), Nov. 6, 1968.

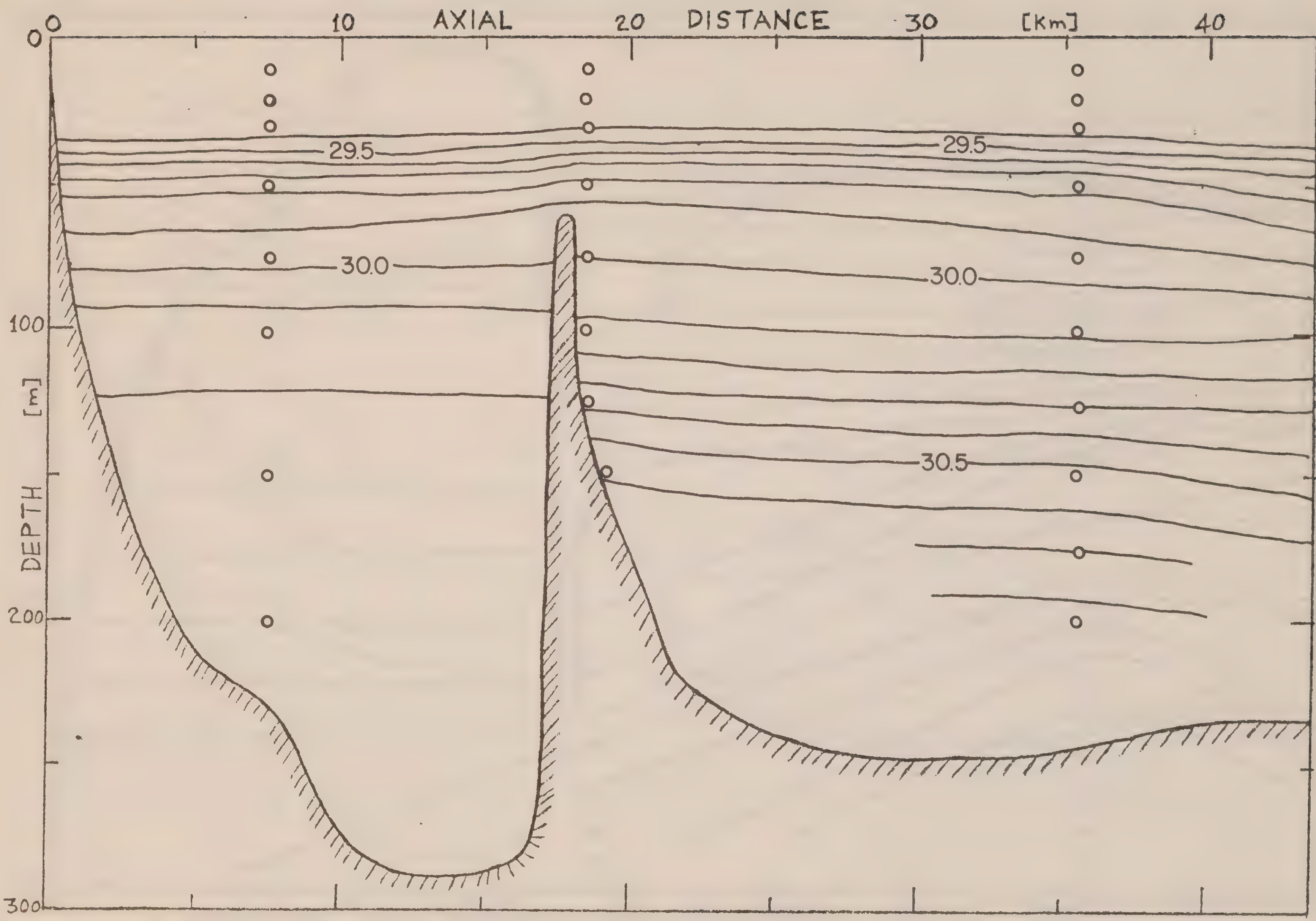

Figure 55. Axial salinity section (from MSB data), Dec. 11, 1968.

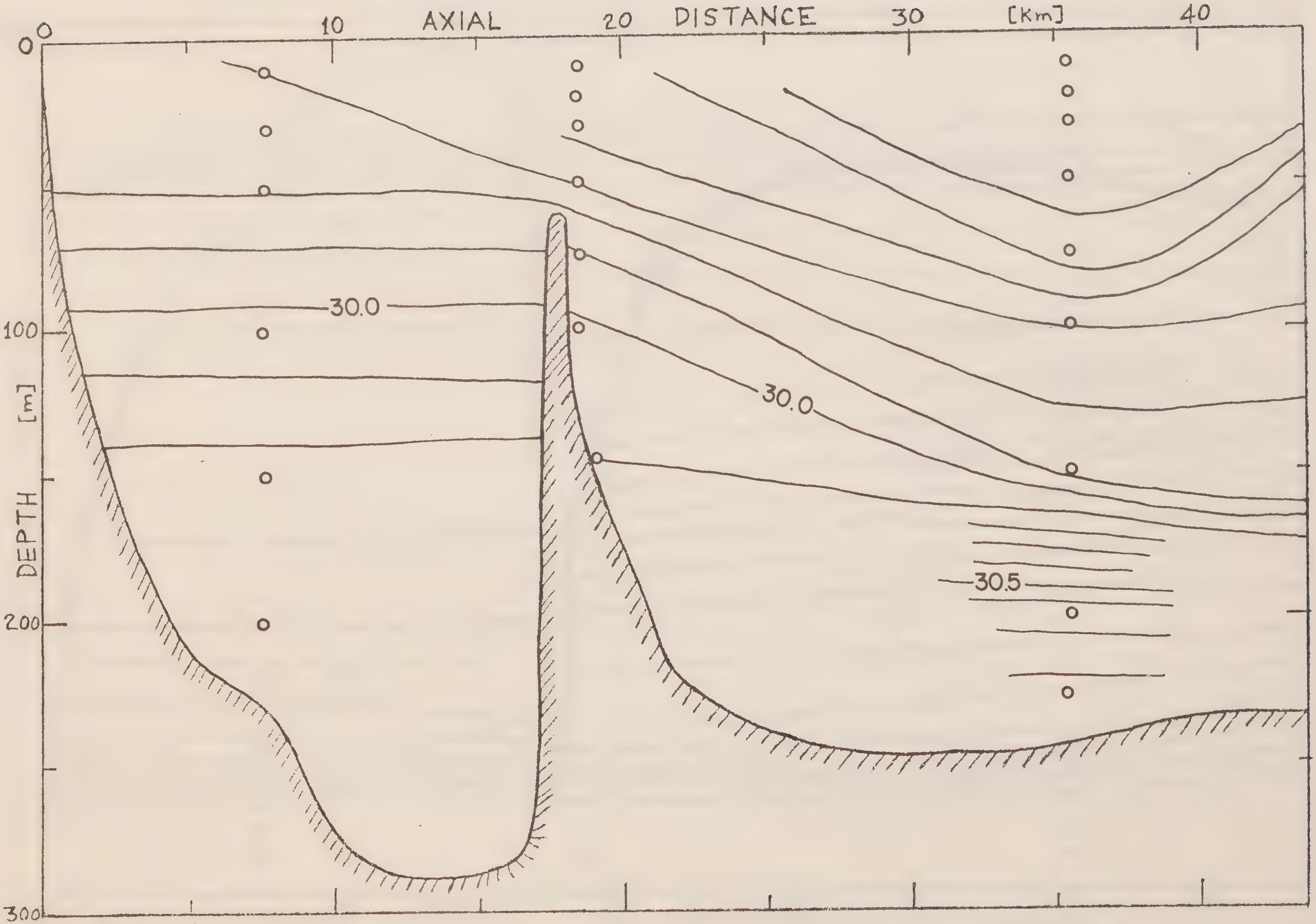

Figure 56. Axial salinity section (from MSB data), Jan. 22, 1969.

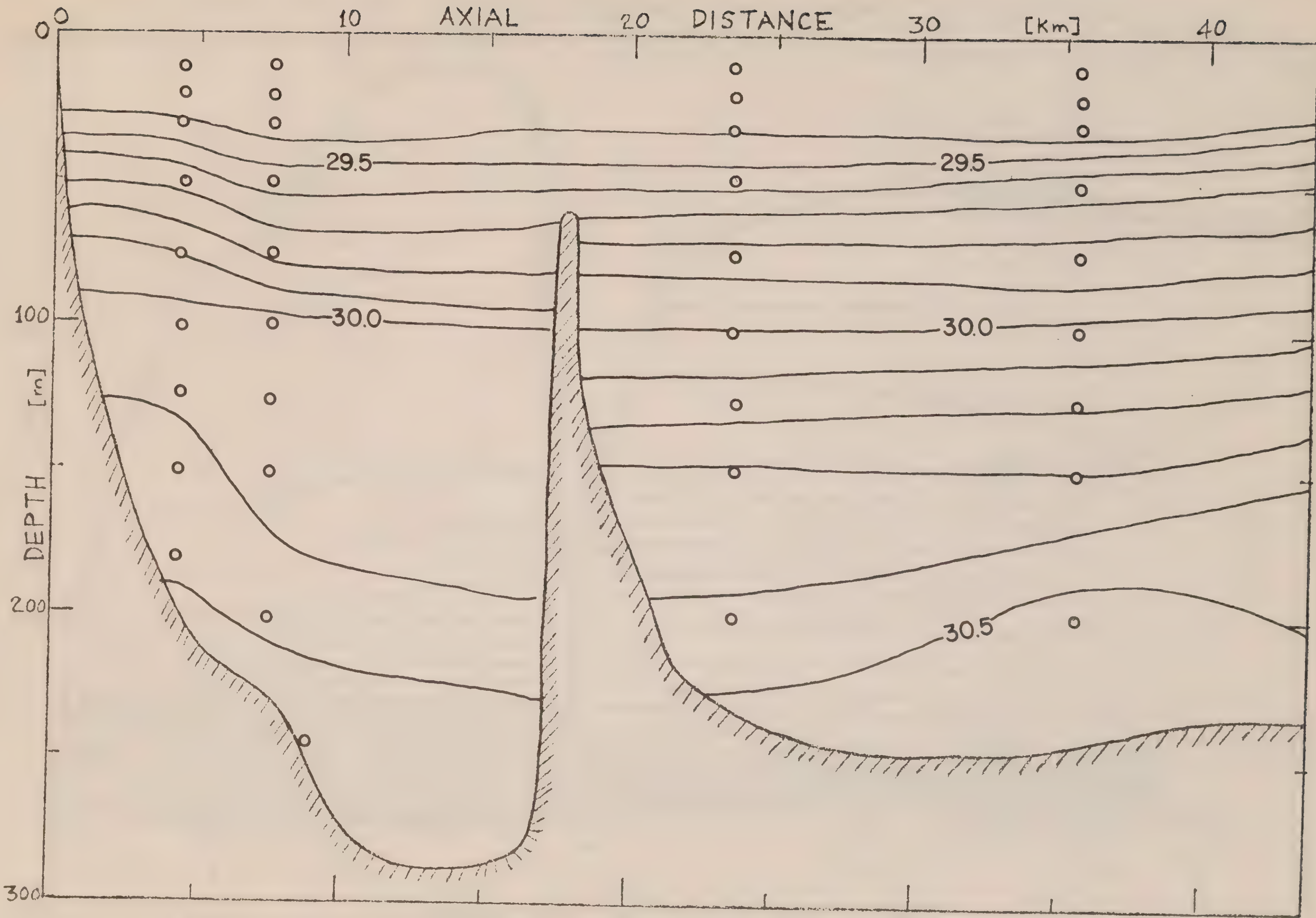

Figure 57. Axial salinity section (from IOUBC data), May 29, 1969.

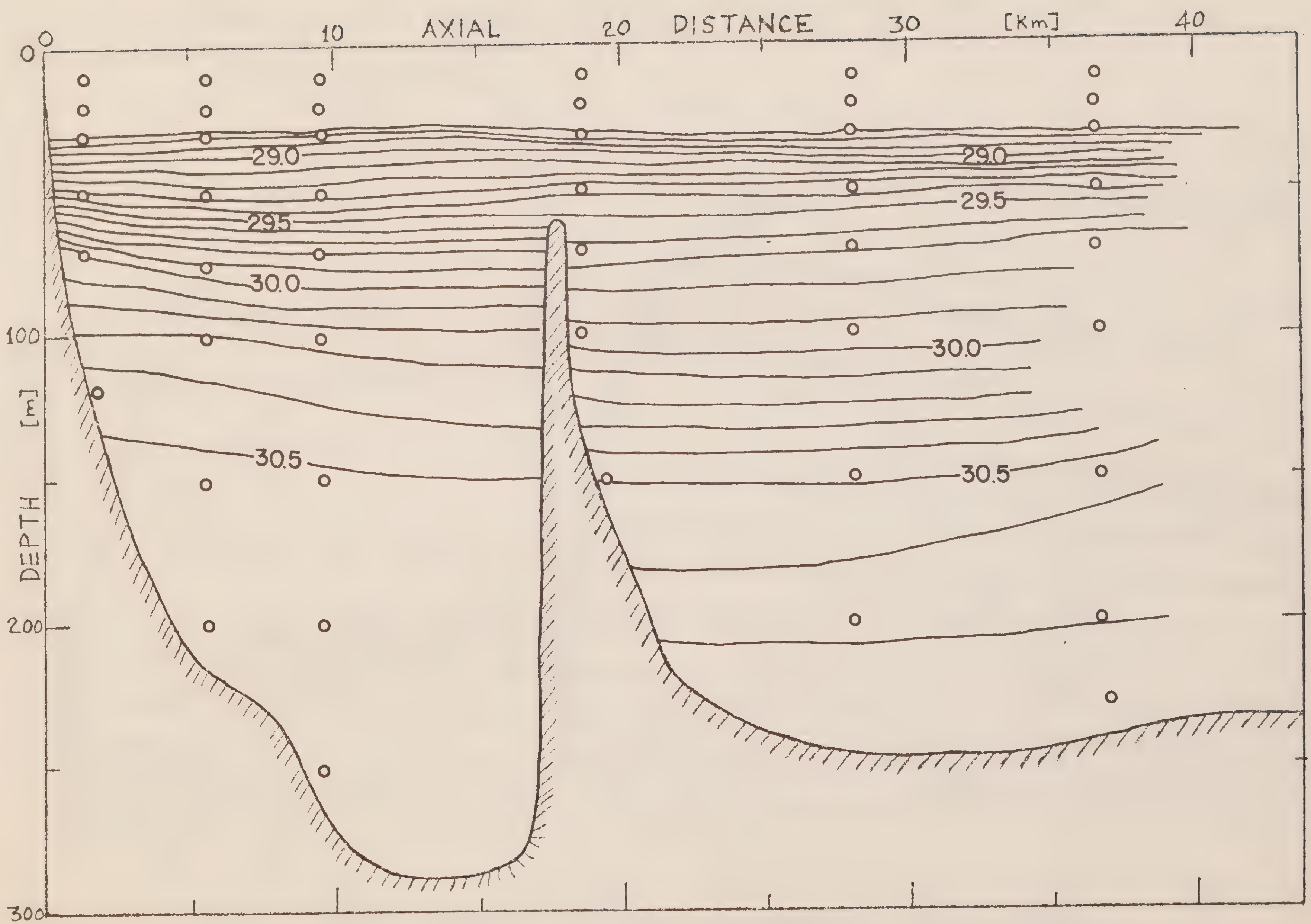

Figure 58. Axial salinity section (from POG data), July 26, 1971.

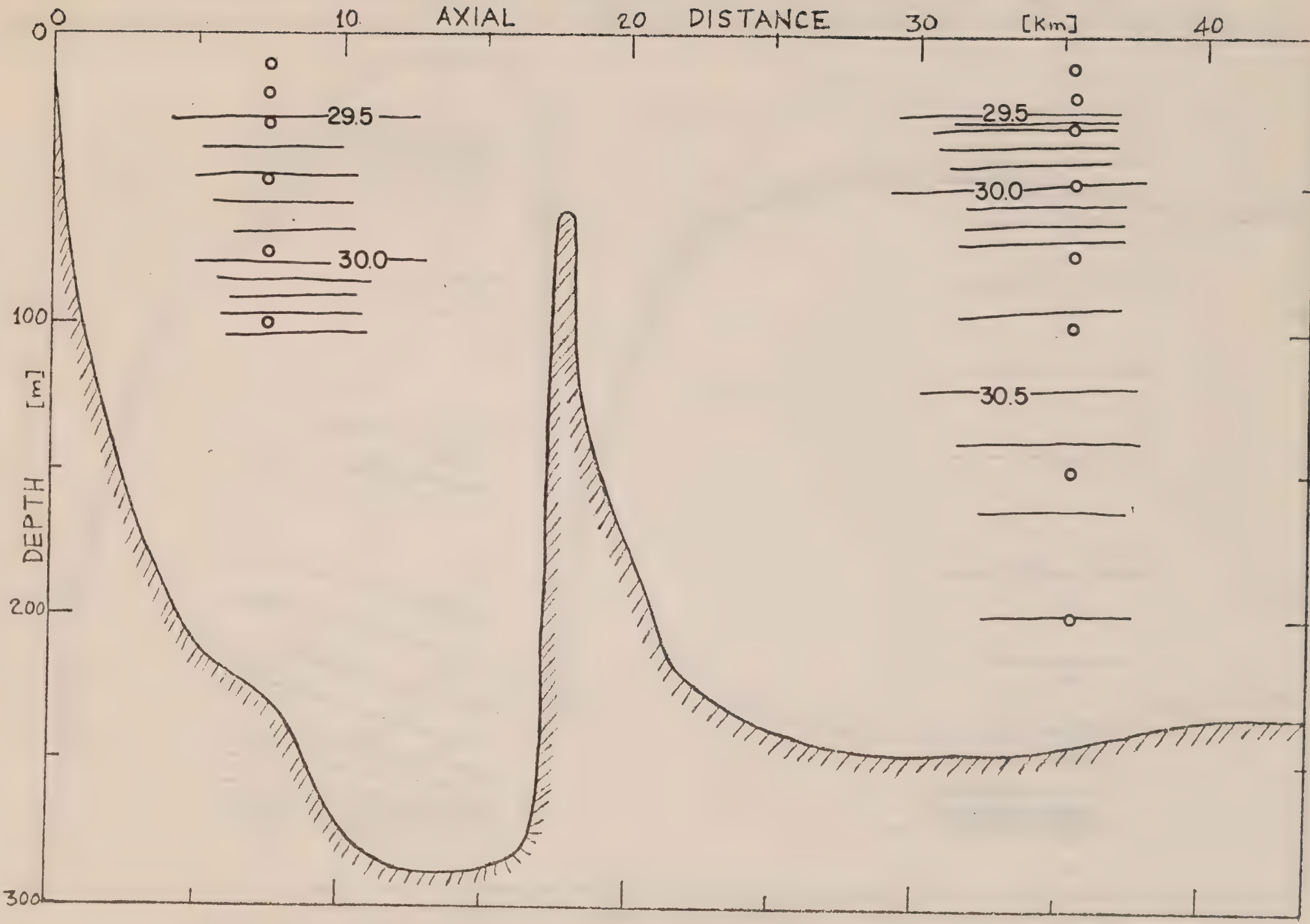

Figure 59. Axial salinity section (from IOUBC data), Sept. 9, 1971.

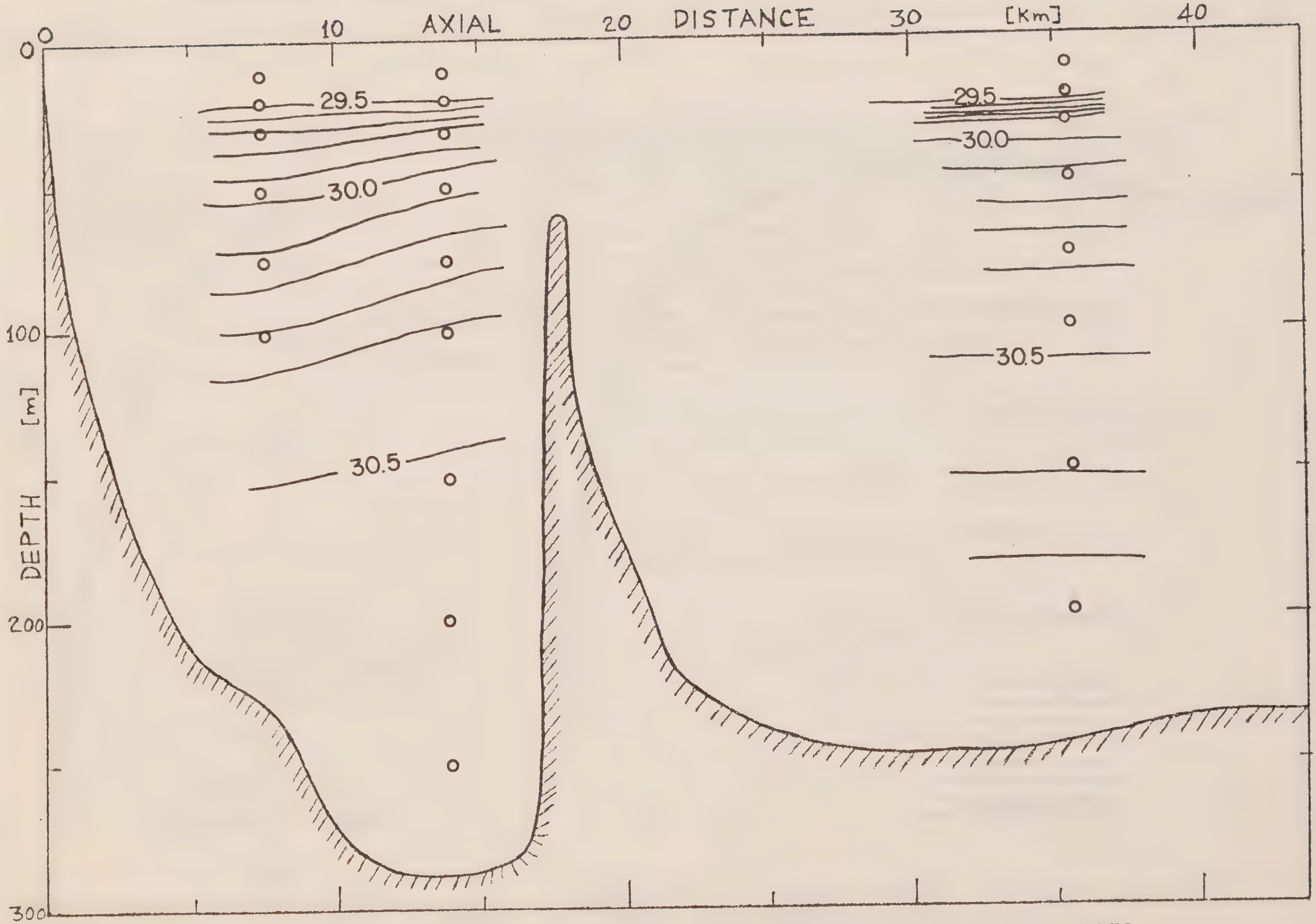

Figure 60. Axial salinity section (from IOUBC data), Oct. 14, 1971.

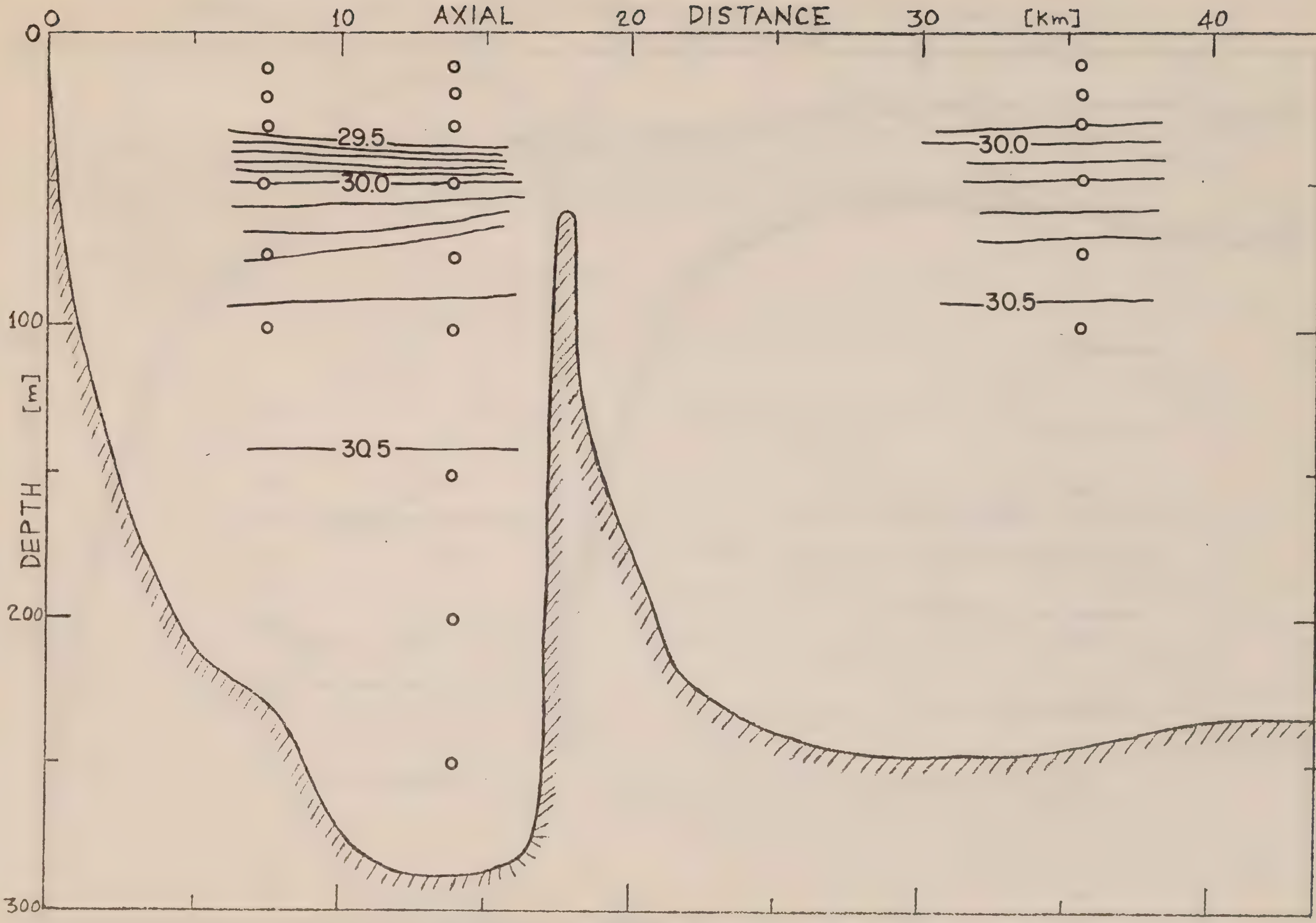

Figure 61. Axial salinity section (from IOUBC data), Nov. 4, 1971.

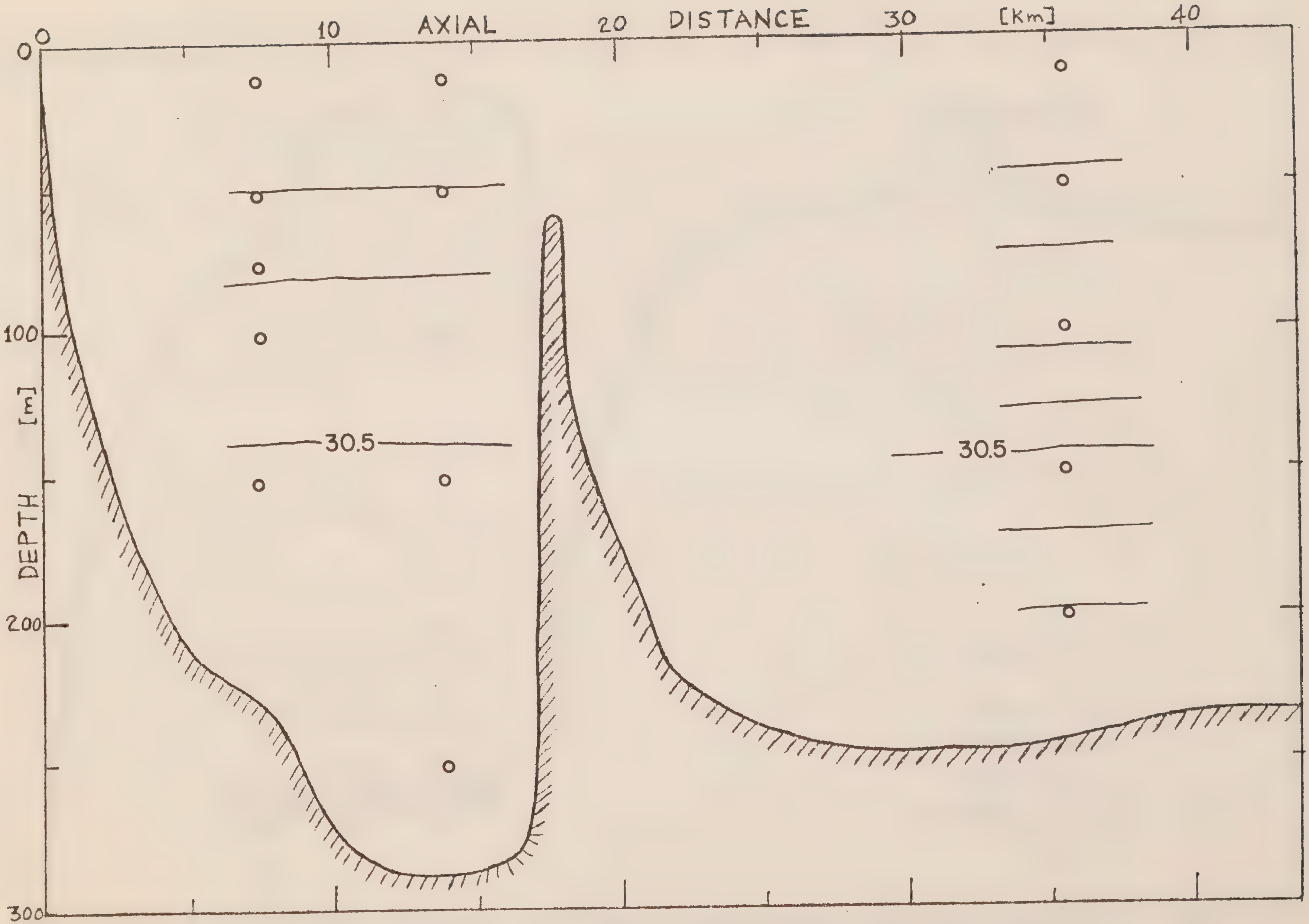

Figure 62. Axial salinity section (from IOUBC data), Dec. 9, 1971.

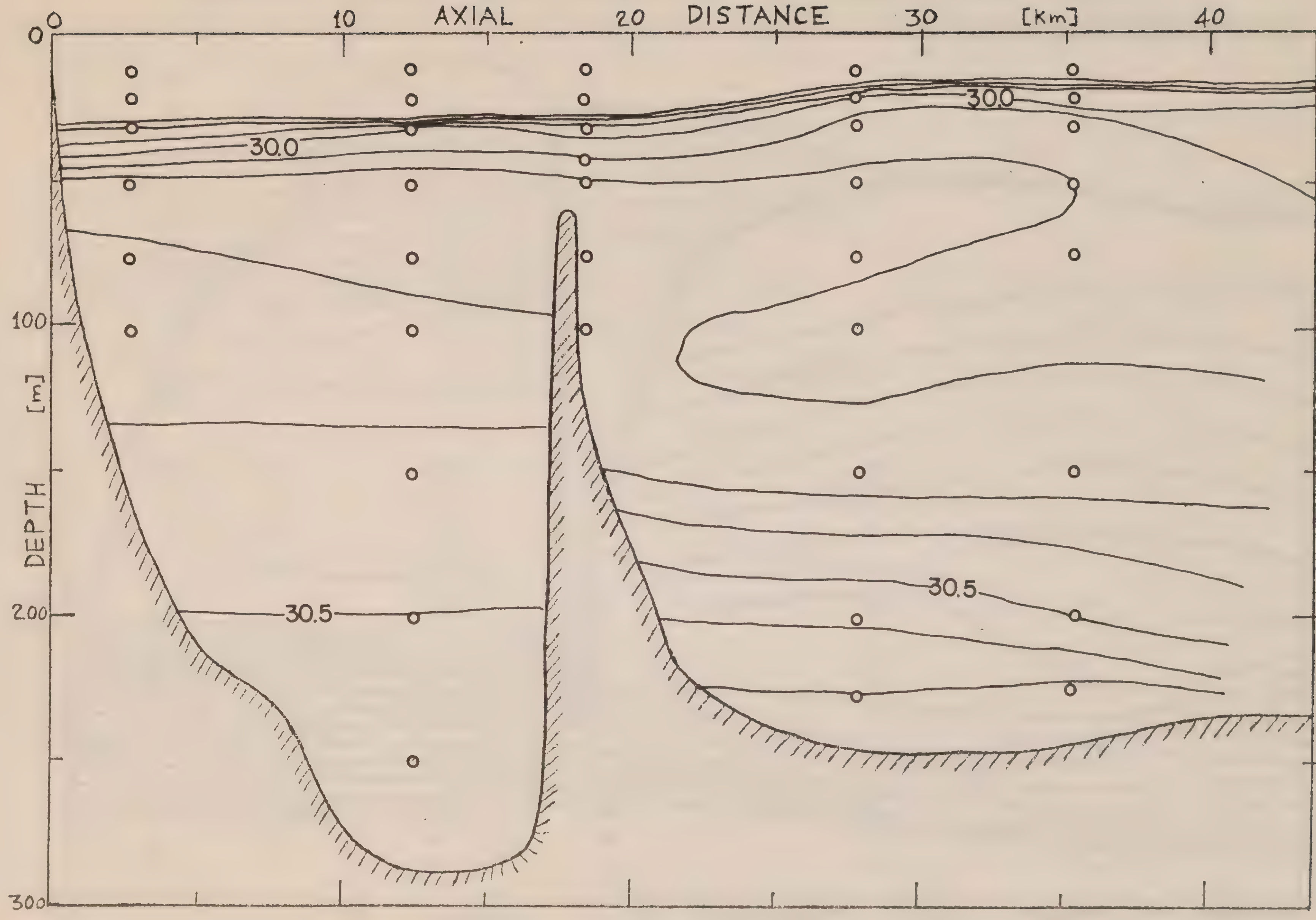

Figure 63. Axial salinity section (from MSB data), Feb. 26, 1972.

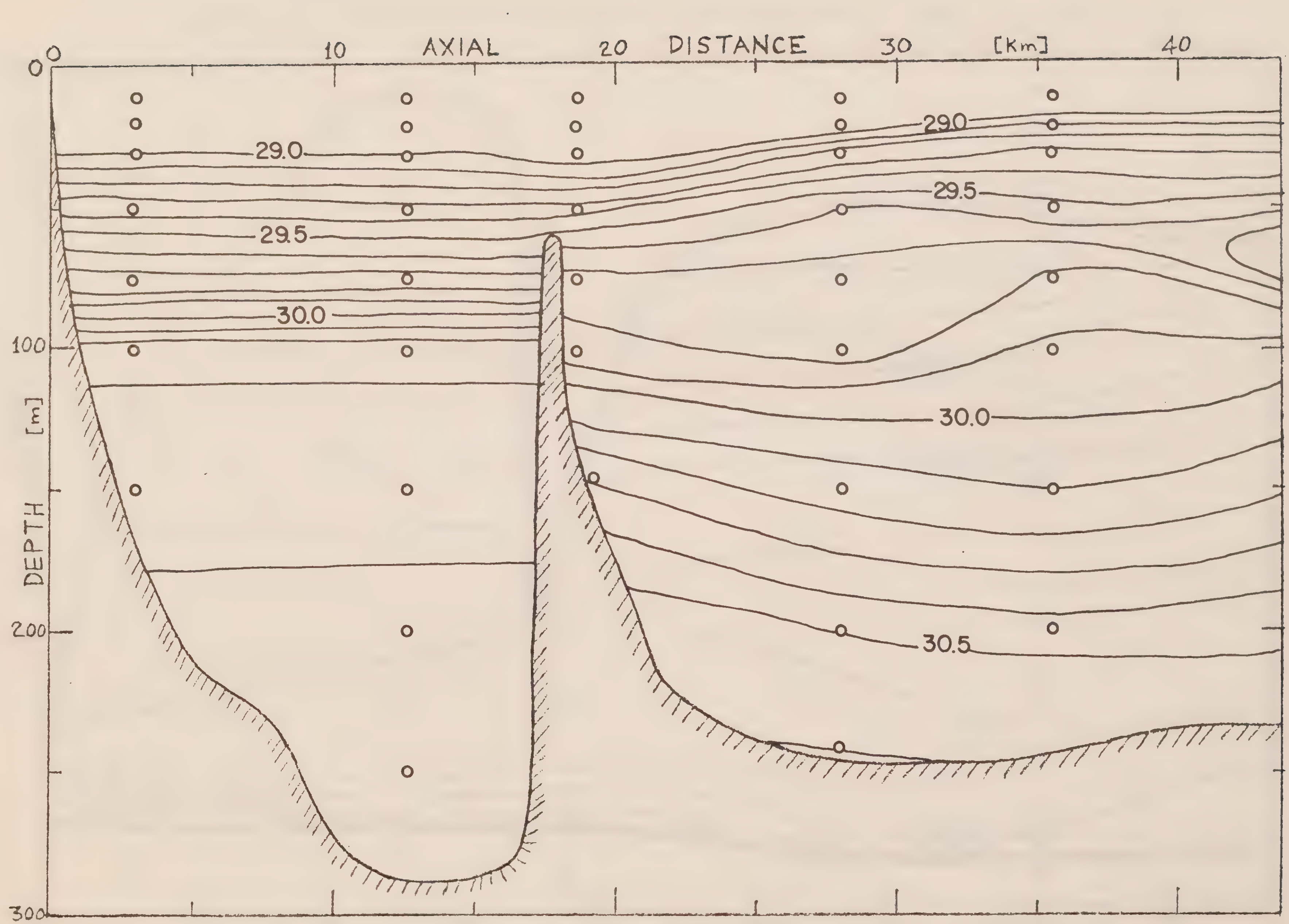

Figure 64. Axial salinity section (from MSB data), June 24, 1972.

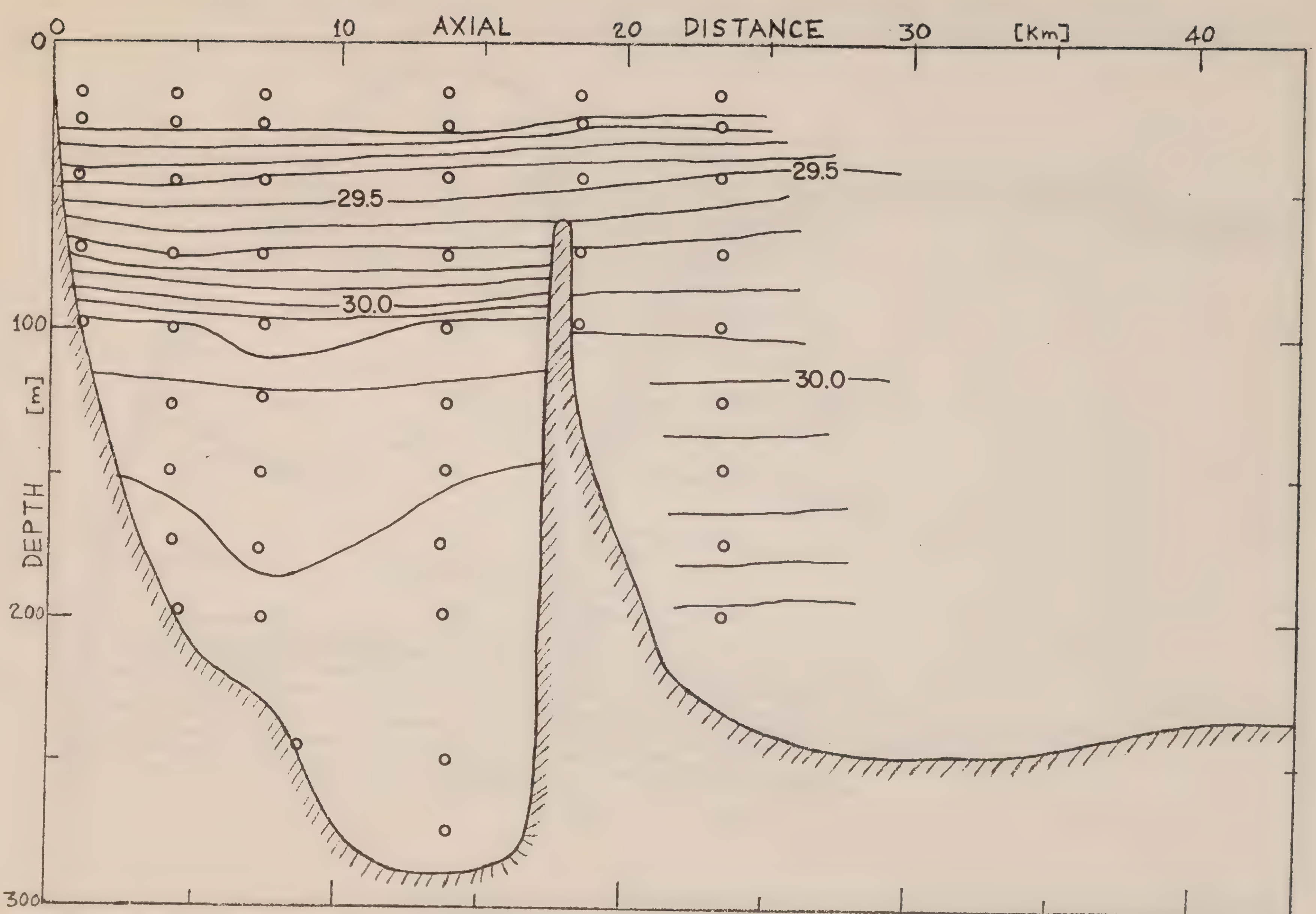

Figure 65. Axial salinity section (from IOUBC data), July 18, 1972.

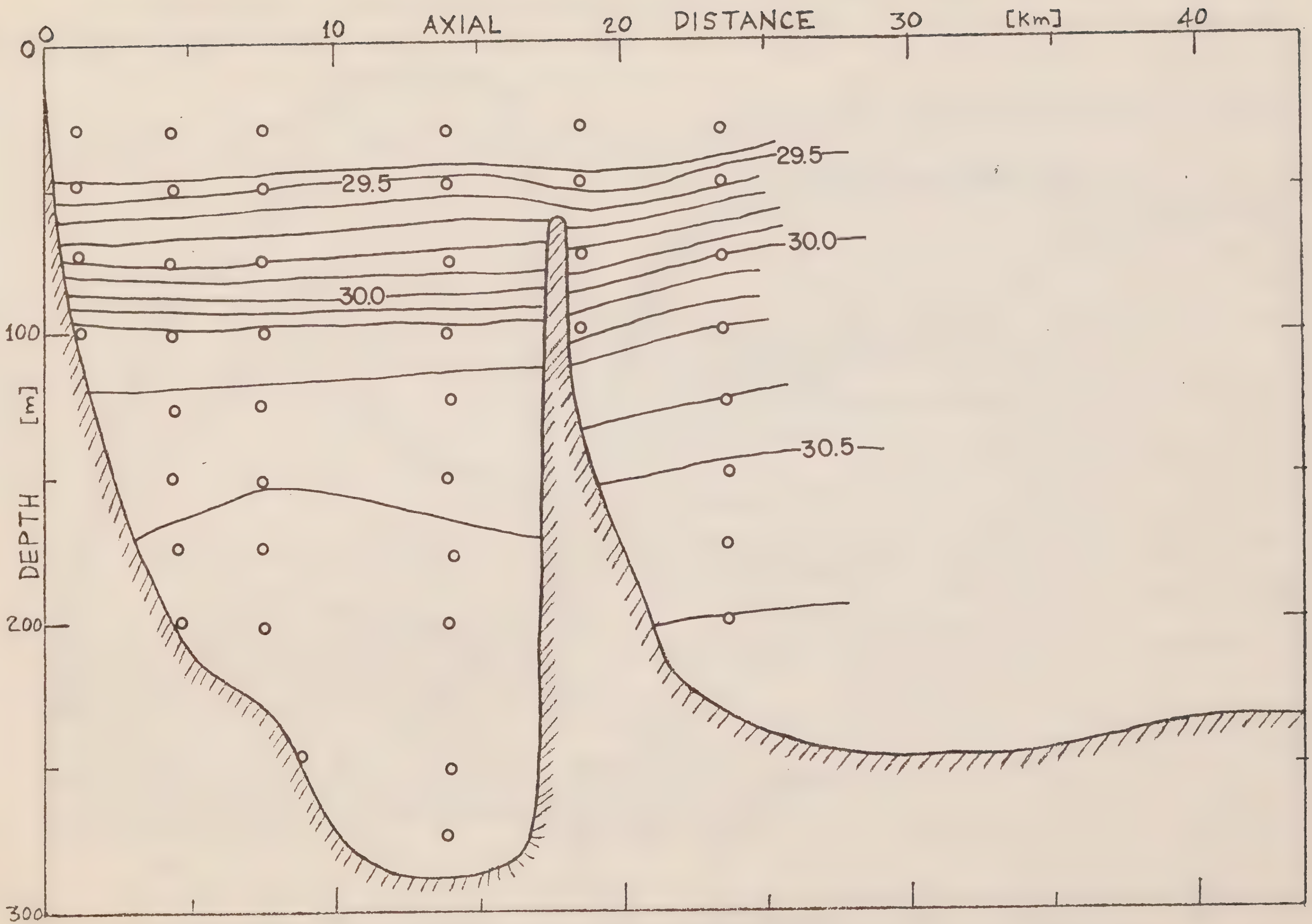

Figure 66. Axial salinity section (from IOUBC data), Sept. 18, 1972.

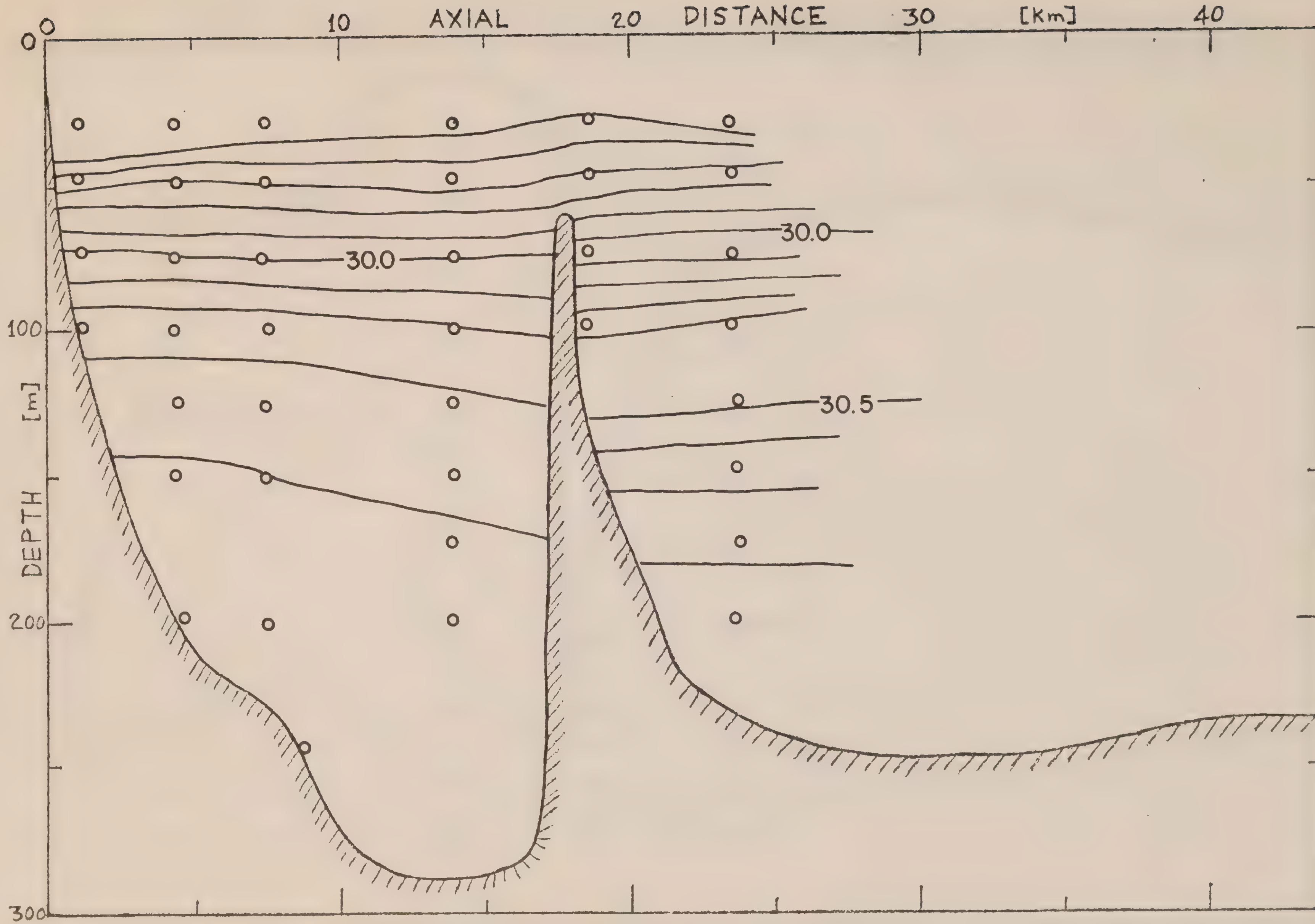

Figure 67. Axial salinity section (from IOUBC data), Oct. 12, 1972.

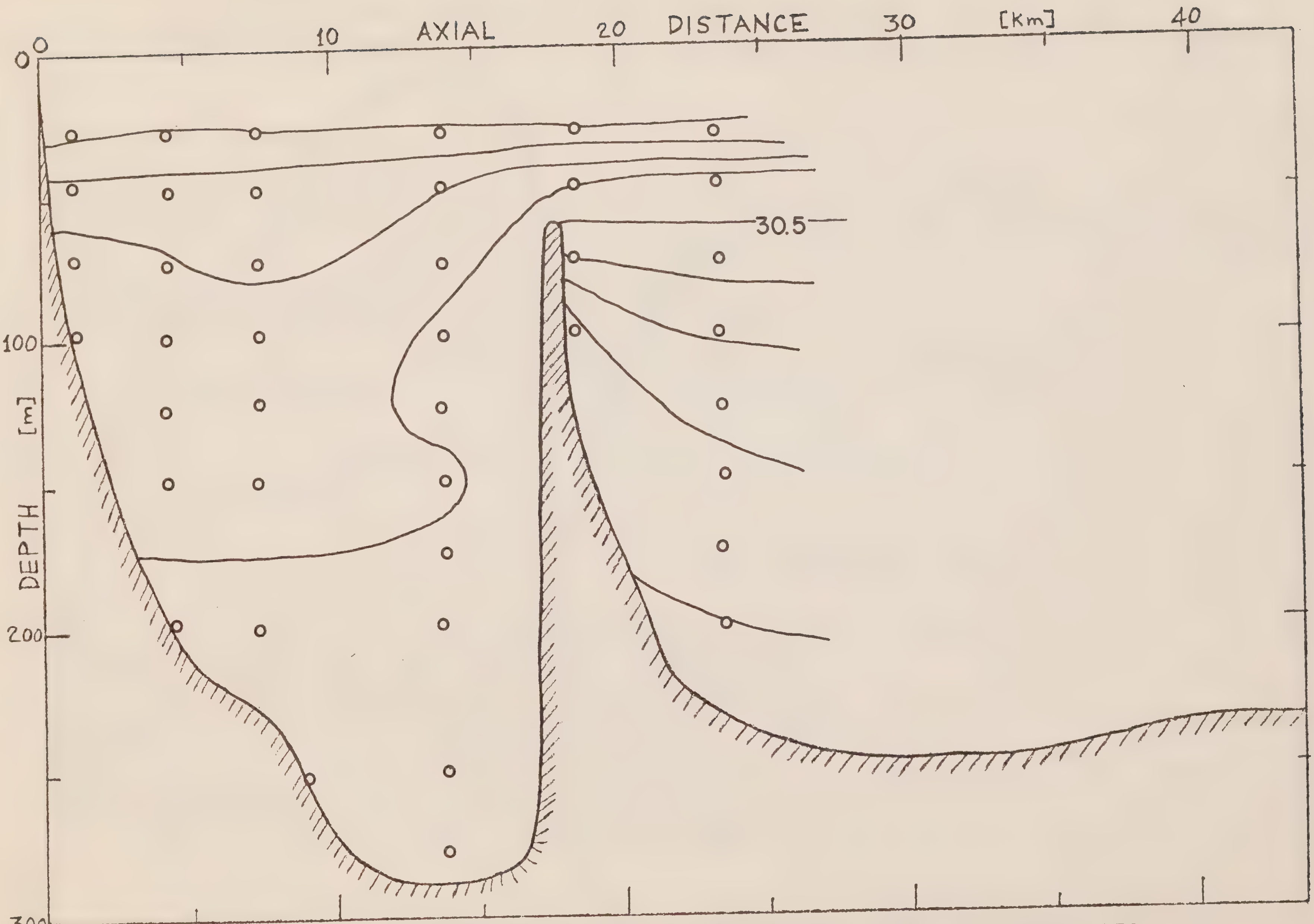

Figure 68. Axial salinity section (from IOUBC data), Nov. 14, 1972.

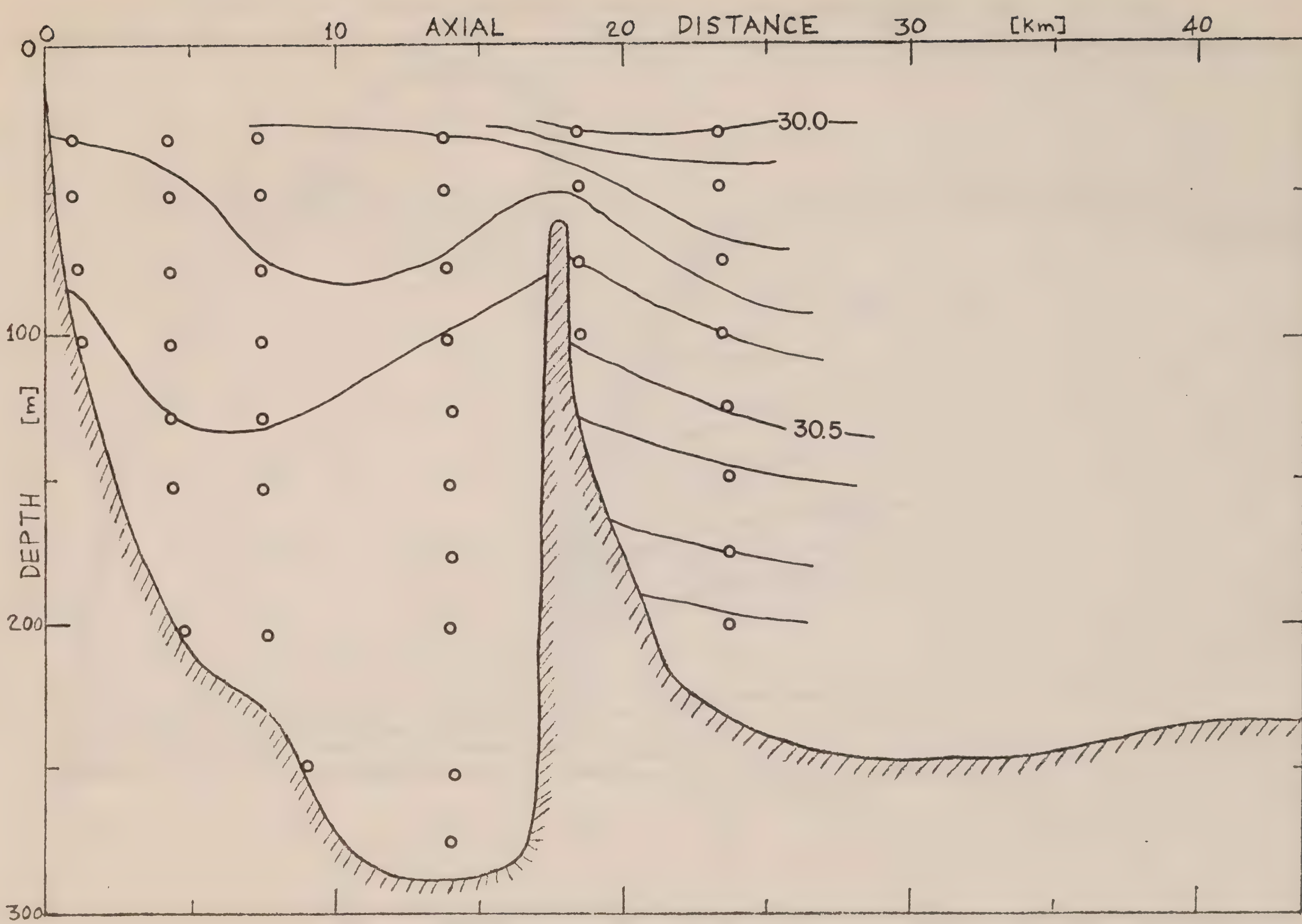

Figure 69. Axial salinity section (from IOUBC data), Dec. 7, 1972.

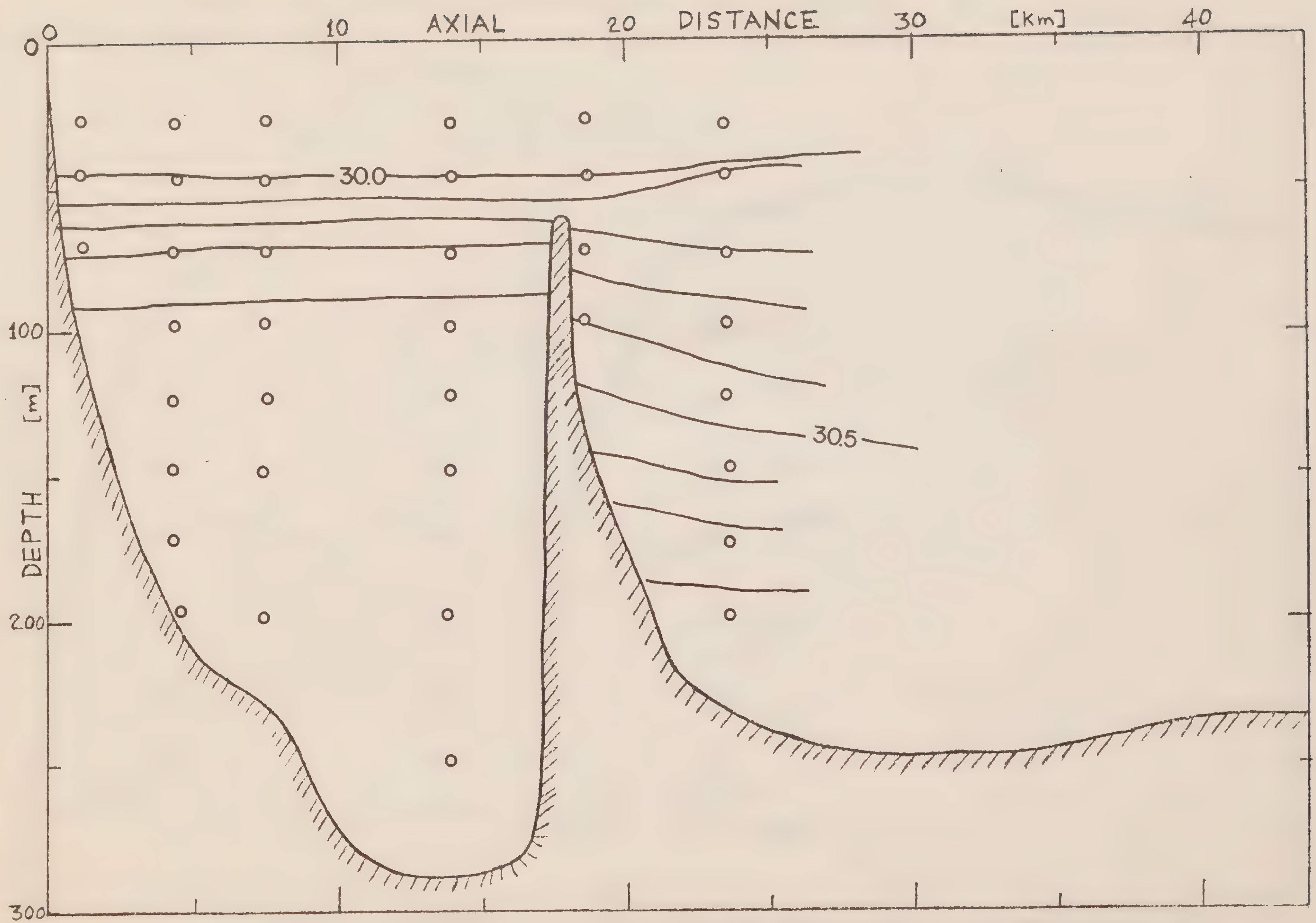

Figure 70. Axial salinity section (from IOUBC data), Jan. 15, 1973.

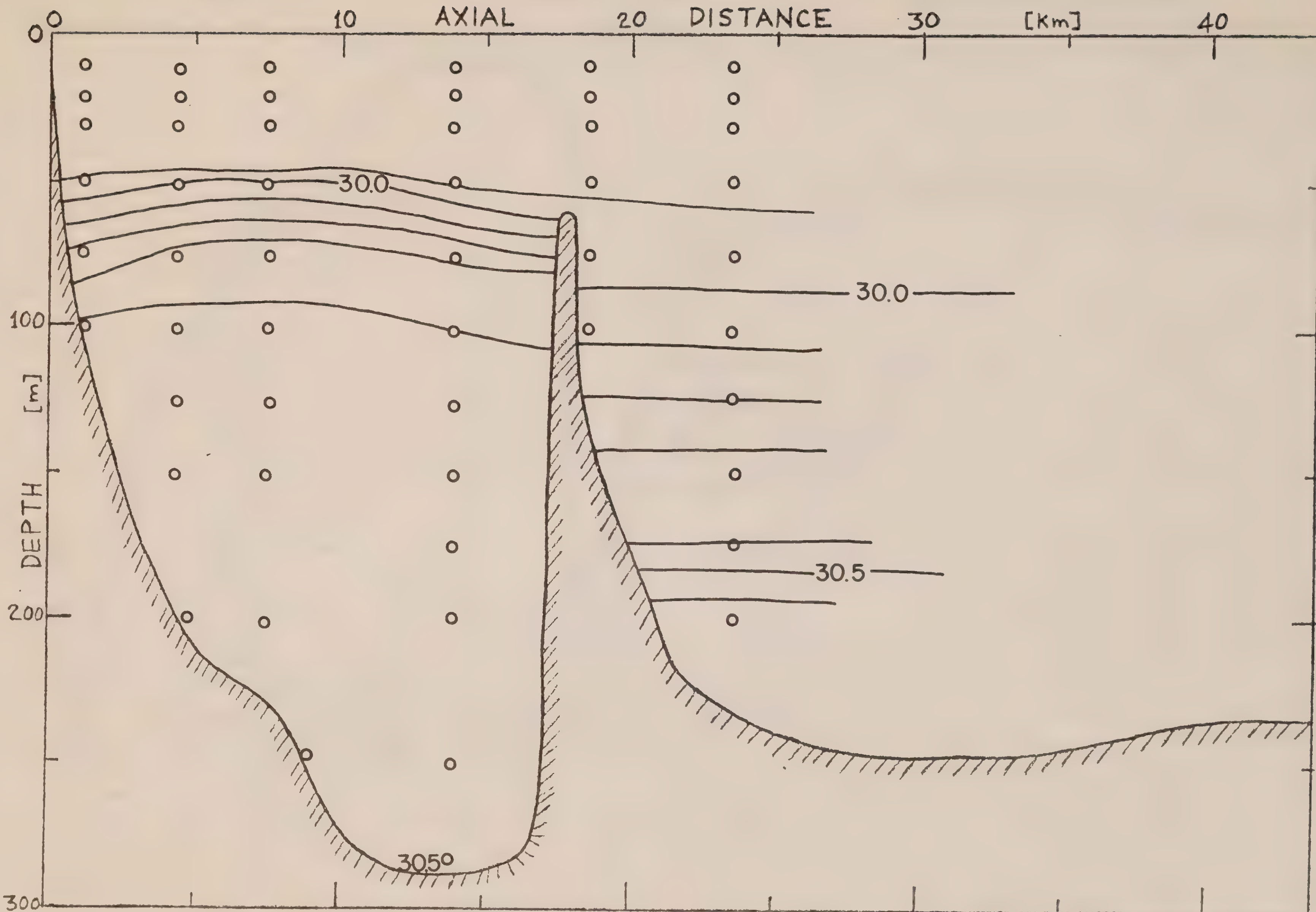

Figure 71. Axial salinity section (from IOUBC data), Feb. 12, 1973.

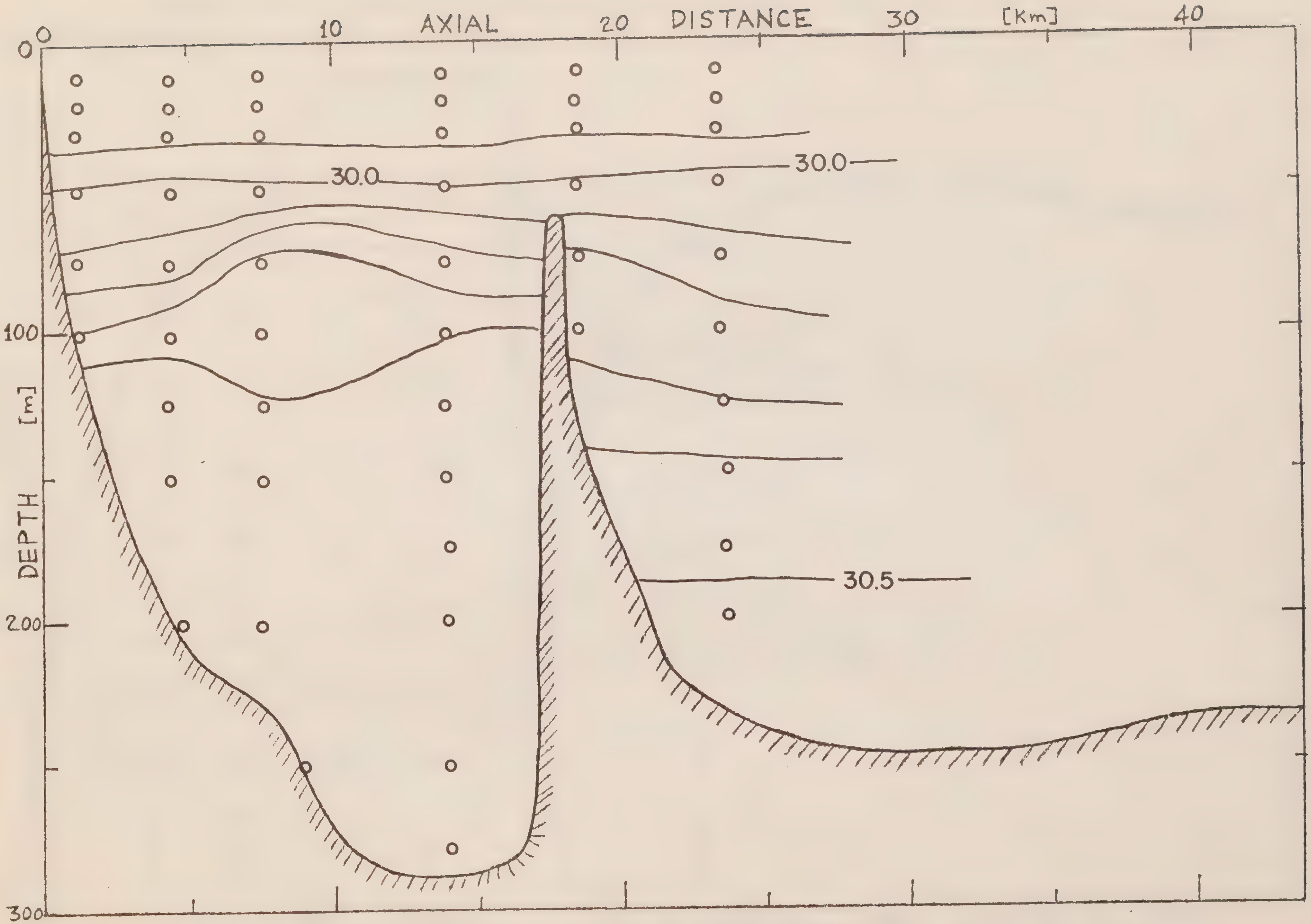

Figure 72. Axial salinity section (from IOUBC data), Mar. 12, 1973.

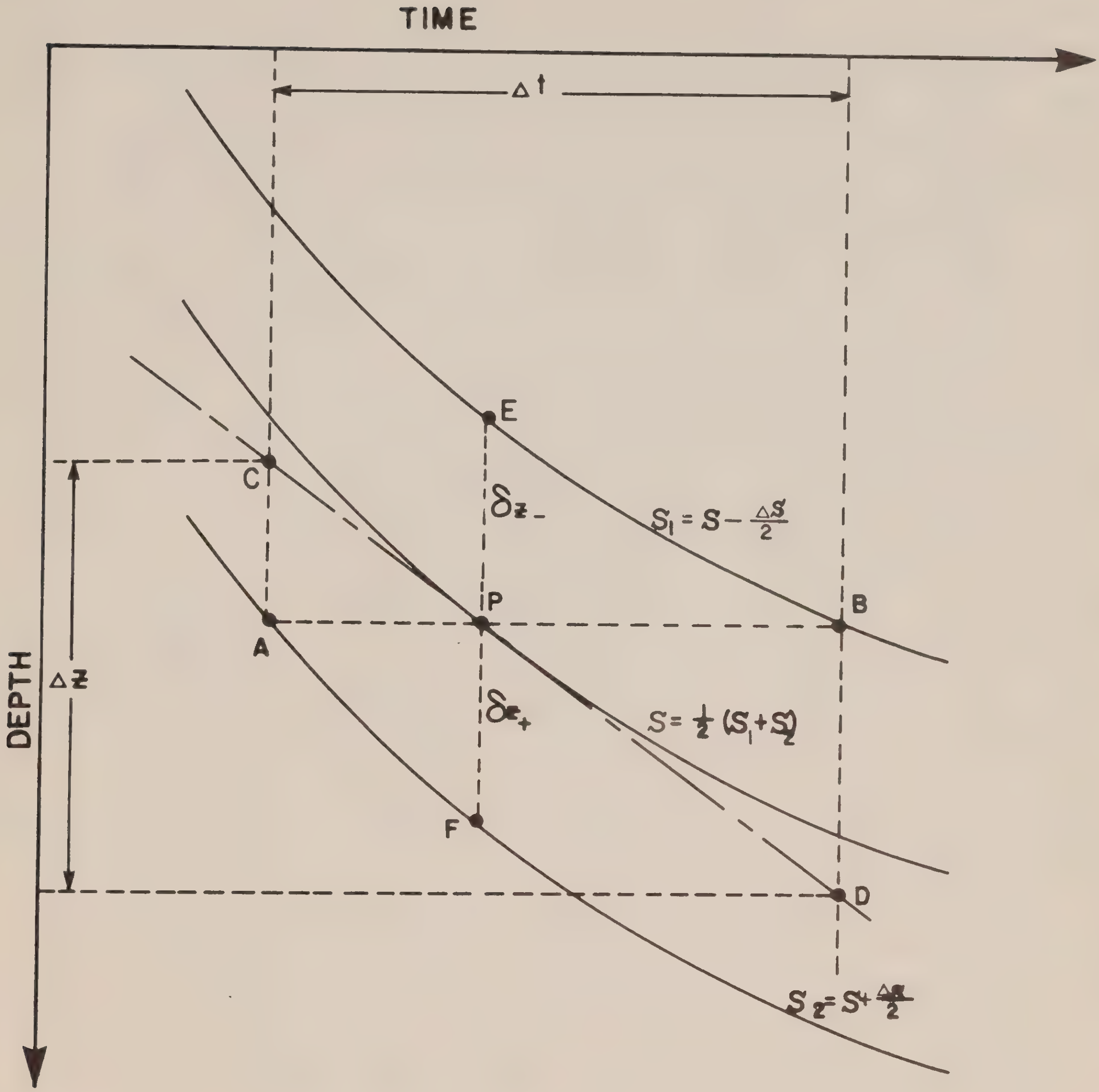

Figure 73. Diagram for the estimation of diffusion coefficients from contours of water property S.